ABSTRACT

SMITH, KELLI L. Linear Concentrated Abrasion Test Method Development for Assessing Performance and Durability of Rescue Hoist Gloves. (Under the direction Dr. Cassandra Kwon and Dr. Bryan Ormond).

Helicopter rescue hoist operators have a specialized need for hand wear to protect against damage from the hoist's cable wire rope—with one hand the hoist operator manipulates a pendant for the hoist controls and physically directs the hoist cable with the other. Currently, a majority of these gloves are made from leather, which possess durability issues as they are destroyed very quickly after only a handful of rescue missions. Aside from the protective failure that occurs when a glove shreds, the leather itself can work its way into the core of the hoist cable, swelling under moist conditions, and potentially fouling the hoist cable. The Department of Homeland Security (DHS) Science & Technology First Responders Group (FRG) identified a requirement for an enhanced rescue hoist glove with improvements in material durability without compromising operator range of motion. Testing of these glove materials and prototypes must include generalized dexterity tests to ensure functionality, while also taking into consideration for the specific type of abrasive conditions experienced with the hoist cable in action. While there are several various abrasion testing methods and specialized abrasion systems in existence, there currently are no abrasion techniques that would accurately simulate the pattern of abrasion incurred from rescue hoist operations. The development of a standardized testing method for concentrated linear abrasion would allow for the collection of useful data that could be used in the comparison between current gloves and developed prototypes, that would result in an improved glove that meets the operator's needs in terms of increased durability and better dexterity. This testing method is developed with a newly designed cable abrader apparatus which can successfully emulate the hoist cable abrasive action.

Linear Concentrated Abrasion Test Method Development for Assessing Performance and Durability of Rescue Hoist Gloves

by
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DEDICATION

I would like to dedicate this thesis to the amazing support system that pushed me to survive and eventually thrive in my academic endeavors, specifically:

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BIOGRAPHY

Kelli L. Smith grew up in the small town of Mayodan, NC, and now lives in Raleigh while attending NC State University. Kelli received her Bachelor of Science in Polymer and Color Chemistry from NC State University in 2017, and after getting her Master of Science in Textile Chemistry in 2019 will pursue a PhD in Textile Technology Management.

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CHAPTER 1 . INTRODUCTION

1.1 Purpose

The linear concentrated abrasion apparatus, or cable abrader, is a new, specialized machine that pulls steel cable rope across a material sample to mimic the abrasive mechanism of a helicopter rescue hoist cable. The main purpose of this work is to develop a test method for the cable abrader apparatus that can produce results that are repeatable and specific to end-use application. Using the developed test method for the cable abrader will allow for a sample material comparison that will accurately simulate hoist operation conditions in a repeatable manner that would not be possible using other abrasion test methods prior to the invention of the cable abrader apparatus. Materials assessed with the cable abrader will be evaluated in terms of abrasion resistance before being integrated in a new rescue hoist glove prototype design.

1.2 Need for Research

Helicopter rescue hoist operators have the critical task of managing the hoist mechanism during flight crew rappelling to an incident, while maintaining focus on flight activity and communications from on-board flight crew. For this action, the operator has one hand on the pendant for the hoist controls and physically manages/moves the hoist cable with their dominant hand. This procedure includes directing the hoist cable in either direction with or without human cargo, pushing or pulling against the hoist cable to compensate for natural movement of the cable due to aircraft motion, and maintaining contact with the flight crew via radio through pendant control. Generally, a standard flame-retardant flight glove as outlined by the Aviation Life Support Equipment Handbook (ALSE) is worn by all of the helicopter rescue crew to protect against flash fires on-board. The hoist operator must also wear an additional glove to specifically protect against the cable[3]. This specialized hoist glove is not standardized, and the type of glove utilized can vary between operators depending on personal preferences. Currently, most of these gloves are made with leather, though the materials of different hoist glove types can vary, as can the durability. Even the most durable glove for rescue hoist operations wear very quickly after only a handful of rescue missions. Aside from the protective failure that occurs when a glove shreds, the leather itself can work its way into the core of the hoist cable, swelling under moist conditions, and potentially fouling the hoist cable. Using a more hydrophobic alternative material to leather with would potentially provide equal durability and maintain the integrity of the hoist cable. The Department of Homeland Security (DHS) released a broad agency announcement (BAA) calling for proposed solutions to this issue, aiming for more durable hoist gloves that also would not reduce the operator's range of motion. One of the gloves currently used by hoist operators can be seen in action in Figure 1.1.

Figure 1.1. Rescue hoist operator controlling hoist cable with gloved hand during live training.

For gloves to be developed to fit DHS's request, the designs need to be carefully tested and scrutinized prior to wear trials by hoist operators. Testing of these glove materials and prototypes must include generalized dexterity tests to ensure functionality, while also considering the specific type of abrasive conditions experienced with the hoist cable in action. While there are several various abrasion testing methods and specialized abrasion systems in existence, there currently are no abrasion techniques that would accurately simulate the pattern of abrasion incurred from hoist operations. Using the cable abrader apparatus with a developed standardized testing method would allow for a side-by-side abrasion resistance comparison of glove prototype materials in terms of both consistent laboratory results and realism to hoist operating conditions.

1.3 Research Objectives

The objectives of this research were to study how the linear concentrated abrasion apparatus (cable abrader) could be used to evaluate glove prototype materials in an environment that simulates conditions in the field, while also being able to show consistent, repeatable results. The hoist glove cable wear pattern is mimicked by applying pressure to the sample via cable tension, and the data is collected in terms of cycles to failure that directly corresponds with helicopter hoist cycles. Utilizing cable rope and abrasive conditions similar to the ones encountered by the hoist operators allows for a more accurate representation of wear/degradation on the glove than could be shown with other abrasion methods or standards. The major objectives of this study include the following:

1. Develop testing procedure for cable abrader apparatus that simulates field stresses in a repeatable manner.
    a. Examine helicopter rescue hoist operations and understand conditions affecting the hoist operator's protective glove.
    b. Review existing standard test methods for abrasion resistance to understand importance of examined variables.

c. Identifying the data sources for the cable abrader apparatus in terms of wear variables.
d. Optimizing running conditions for the cable abrader to reach consistent results.

2. Utilize cable abrader with the developed test method in comparison testing of current and future hoist glove materials.
    a. Identify materials in terms of baselines that are representative of hoist gloves and leather alternative materials.
    b. Test baselines and alternative materials using linear concentrated abrasion test method.
    c. Compare test results obtained with the linear concentrated abrasion test method for all materials.
3. Compare different abrasion test methods and apparatuses for representing abrasions hoist operations to evaluate abrasion resistance of baseline materials and prototype materials.
    a. Review all relevant test methods related to abrasion resistance of textiles and decide most representative of hoist cable action theoretically.
    b. Measure abrasion resistance of baseline materials using ASTM standardized methods, including Taber® abrasion machine and Wyzenbeek abrasion machine.
    c. Compare standard test methods with cable abrader's linear concentrated abrasion test method in terms of hoist operation representation.

In accomplishing these objectives, the missing areas will be highlighted in current abrasion test methods related to functional use in hoist rescue operations, and the capabilities of the cable abrader apparatus will be better understood and developed.

CHAPTER 2 . RESCUE HELICOPTER HOIST OPERATIONS

2.1 Rescue Helicopter

There are various types of airframes used to perform hoist rescue operations. Two common airframes for helicopter rescue operations include the UH-60 Black Hawk rescue helicopter and the UH-72A Lakota rescue helicopter (Figure 2.1).

Figure 2.1. (Left) UH-60 Black Hawk rescue helicopter and (Right) UH-72A Lakota rescue helicopter airframe.[1]

Called in to assist with emergency situations where other responders are not able to access, rescue helicopters hold relatively small amounts of passengers compared to more commercial or military transport type aircraft. Aside from normal helicopter mechanical components, the rescue hoist helicopter has a mechanical hoist system that can be either internally or externally connected, as seen in Figure 2.2.

Figure 2.2. UH-60 Black Hawk internal hoist system (left) & UH-72 Lakota external hoist system (right).

For rescue helicopter hoist systems, cable failure means an unexpected reduction in resources in emergency response to a scene, as well as the potential for injury or death. To reduce the chance of a cable failure, the hoist cable in rescue helicopters are checked after every mission, as well as replaced after a certain number of cycles regardless of the actual working state of the cable. For most rescue helicopter models, this number is approximately 1500 complete cycles before the hoist manufacturer will come and swap the cable out for a brand new one [2].

2.2 Rescue Helicopter Crew Members

For helicopter rescue missions, the aircrew present can vary between military and private agencies. Generally speaking, there are at least four members of the aircrew present, including the pilot, copilot/helicopter manager, the operations crew chief, and the rescue technician [29]. Each member of the aircrew is responsible for a different set of tasks related to the rescue mission, from flying the helicopter to interacting with the subjects being rescued. A short description of each member's responsibilities can be seen in Table 2.1.

Table 2.1. Rescue Hoist Helicopter Aircrew Member Positions

Job Title	Responsibilities
Pilot	All activities that are related to flying the helicopter
Copilot	Navigation to the rescue site and maintaining communication between the aircrew, with pilot monitoring; can also be known as the helicopter manager
Hoist Operator	Operations in the rear portion of the helicopter cabin, in this case hoist operations; can also be known as operations chief, crew chief, or spotter.
Rescue Technician	Performs rescue tasks related to the hoist, such as helicopter rappel operations and/or patient care. The rescue technician, or rescuer, also maintains communication to keep link between rescuers at the scene and the aircraft [30].

Figure 2.3. Hoist operator (left, holding cable), rescuer (center), and copilot (right) during training exercises.

2.3 Rescue Hoist Operator Tools

For a rescue hoist operator to be able to do their job properly, there are some pieces of equipment and tools that must be employed, ranging from standard issue to specialized equipment. The following sections detail the items necessary for rescue hoist operations.

2.3.1 Standard Helicopter Crew Personal Protective Equipment

Due to the increased risk associated with working on a moving aircraft, the United States Department of the Interior (DOI) and the Occupational Safety and Health Administration (OSHA) have set requirements for personal protective equipment (PPE) in order to provide head protection and flash fire protection. Specific PPE includes a flight helmet, fire-resistant clothing, protective gloves, and boots [31].

2.3.1.1 Flight Helmet

According to the Aviation Life Support Equipment (ALSE) Handbook, a helmet for helicopter flight must be approved by U.S. military standards or conform to the American National Standard Institute (ANSI) standard Z90.1B-1992 [ref #, ANSI Z90.1B-1992]. The helmet is worn during flight to protect from head trauma, and functions as a headset for radio traffic between flight crew members. In Figure 2.4, the helmet for a helicopter hoist rescue operator is shown with face mask attached, as well as radio functionality.

Figure 2.4. Flight helmet configuration for helicopter hoist rescue operator.

2.3.1.2 Fire-resistant Clothing

The ALSE Handbook specifies that all clothing worn by the aircrew must be flame resistant, from the outwear down to the undergarments. Wearing items for outerwear that are made from natural fibers, like leather, cotton, wool, wool/cotton blend, flame resistant (FR) cotton blends are also acceptable [3]. Synthetic materials like nylon, Dacron, polyester, or synthetic blends are not approved due to the possibility of flash fire injury from the material melting to the skin. Length of garments are also specified in the ALSE handbook, saying that flight suit coveralls must fit loosely, but have sleeves long enough to reach the first knuckle of the hand and pant legs reach the floor while standing and to the ankle while sitting [3]. An example of the flame-resistant flight suit can be seen in Figure 2.5.

Figure 2.5. Flame resistant flight suit worn by helicopter aircrew [32].

2.3.1.3 Flight Gloves

Flight gloves are worn by all crew members aboard the rescue helicopter. The gloves are generally composed of a soft leather that covers the inside of the palm, fingers, and wrist, with the rest of the glove made of a stretchable fire-resistant material like Nomex® to protect the wearer from flash fire during flight. The general type seen are called “summer flyer” gloves due to the light feel of the glove compared to heavier cold weather gloves, which can be seen in Figure 2.6.

Figure 2.6. Summer flyer style flight glove worn by rescue helicopter aircrew.

For these flight gloves, dexterity is of the utmost importance since the aircrew must be wearing them at all times onboard the helicopter [3]. There is no specific standard for the basic flight glove aside from those guidelines (other than uniform color specifications) which could be seen in the wide range of glove types used by flight crews.

2.3.1.4 Boots

The ALSE handbook always requires that protective footwear in the form of specialized boots be worn in the aircraft. These boots must have the tops extend above the ankle and must be constructed so that metal components (shoestring eyes, zippers) do not contact the wearer’s skin. The type of boots worn are determined by the weather conditions, specifying cold, temperate, and hot options in the ALSE handbook. Leather boots are preferred, but some non-leather boots are authorized and outlined in the handbook as well [3].

2.3.2 Helicopter Hoist Equipment

Aside from the gear and attire required for all aircrew members, the hoist operator also has some specialized pieces needed to perform their job.

The hoist operators in the Black Hawk rescue helicopter work on their knees, leaning forward to manipulate the cable position. In contrast, the UH-72 Lakota uses an overall stationary external hoist system, with the hoist operator tethered, sitting out of the side of the aircraft (refer back to Figure 2.2). An additional feature of the controller involved triggering radio communication via squeezing the handle of the hoist controller (Figure 2.7). While both utilized the same diameter of hoist cable, the variances between the airframes surfaced in slightly different techniques in the hoist handling for each operator. The oscillation of the cable, aside from the basic up/down iterations of the hoist, appeared as a challenge for both the operators and for the hoist glove itself to overcome.

Figure 2.7. Helicopter hoist control pendant.

2.3.2.1 Hoist Operator Glove

In addition to the flight glove worn, the hoist operator also needs to wear a rescue hoist glove to protect against the abrasive hoist cable. The ALSE requires that all helicopter rescue crew members wear flight gloves to protect against flash fires on board, and the hoist operator wears an additional glove to protect against the cable [2]. The flight gloves outlined in the personal protective equipment (PPE) section are either all-leather, or leather and Nomex®, which meet the flash fire resistance and dexterity needs of the rest of the flight crew, but are not durable enough against abrasion from the hoist cable for the hoist operator to wear alone. Leather is a natural material that is inherently variable in the amount of abrasion resistance it provides because of the susceptibility to moisture and variation in fibers due to its natural structure [33]. When the leather material fails, the glove is not only destroyed, but the shreds of leather can work into the cable causing fouling and potentially failure. Aside from the variability of leather on a material level, leather hoist gloves vary designs and thicknesses between companies.

2.3.2.2 Hoist Glove Experiences

In preliminary gathering of information prior to this research, rescue helicopter crew members shared their thoughts on hoist gloves between rescue hoist training exercises. The overarching note was that there was not a “standard” in terms of a protective glove or wear configuration that the responders, which resulted in the use of a wide variety of both specialized and non-specialized gloves.

Even so, two particular extremes emerged for the glove types used. One hoist glove type excelled in terms of dexterity and comfort but would fail very quickly in as little as one mission; another type examined lasted significantly longer in terms of use, but was so stiff that a day’s worth of “breaking in” was required before the operator would be able to use it somewhat comfortably. Utilizing materials other than leather provides an opportunity to alleviate the issue with cable fouling, while also providing a “better” glove in terms of consistency of wear and dexterity.

Another unexpected observation was the relatively short duration that even the more expensive hoist gloves appeared to last. One of the currently used higher end gloves only lasted 12-13 iterations of three raising/lowering the cables before severe wear or a complete failure appeared. The owner of the higher end hoist glove reiterated the need for a glove with equal or improved durability, without losing any dexterity from the stiff over glove.

In the following section, the various considerations to understand the specific abrasion caused by a hoist cable in terms glove material response are discussed.

Figure 2.8. Over glove style hoist glove worn without flight glove underneath.

2.4 Essential Hoist Glove Qualities

Hoist operations require a glove with a unique balance between several necessary qualities. Most importantly, the glove must be resistant to abrasions caused by the hoist cable and operations, while also being flexible enough not to hinder the range of motion for the operator.

2.4.1 Abrasion Resistance and the Importance of Durability

For a hoist glove, the main purpose is to give protection from the wire cable rope to the hoist operator that cannot be satisfied by the flight glove alone. The glove worn needs to be made of a material that can withstand the concentrated linear abrasion caused by the hoist cable moving across the surface of the palm and fingers. As seen in Figure 2.9, abrasions will tend to show in the thumb gusset and finger regions where constant contact occurs with the hoist cable during rescue operations.

Figure 2.9. Hole caused in work glove via thumb gusset abrasions.

Glove wear pattern expectations included the thumb gusset area of the hoist glove as outlined in the requirements for the project. In observation, while the thumb gusset area was generally the most worn area, parts of the fingers and stitching were compromised as well. One of the cheaper work gloves accumulated wear in the thumb gusset area, and the higher end hoist glove on the right with wear in both the thumb gusset and in the finger area. With the over glove style, wear would also show for the summer flyer depending on the way the hoist operator worked. The flight gloves required by the ALSE, summer flyer type Nomex® gloves showed concentrated wear on the fingertips and at the seams on the sides. As mentioned previously, the type of hoist also appeared to have affected the wear style slightly due to the difference in positioning of the operator [3]. No two hoist operators appeared to handle the apparatus exactly the same way, though the wear patterns were observed in the same few areas. Hoist operators also can choose the style of protective glove configurations, either choosing to use a full-fingered integrated glove, a fingerless over glove worn with flight glove underneath, or the fingerless glove worn alone. The full integrated glove provides protection for the entire hand, though sometimes at the cost of dexterity due to the bunching of materials at the ends of the fingers. The over glove provides versatility to the operator in terms of configuration choice with one option as the over glove snuggly on top of the flight glove as seen in military regulations, or another as with the over glove worn alone with fingertips bare to physically monitor the hoist cable for damage as rescue operations are in progress. In Figure 2.10, the hoist glove graphic is shown in stand-alone and under-glove configurations.

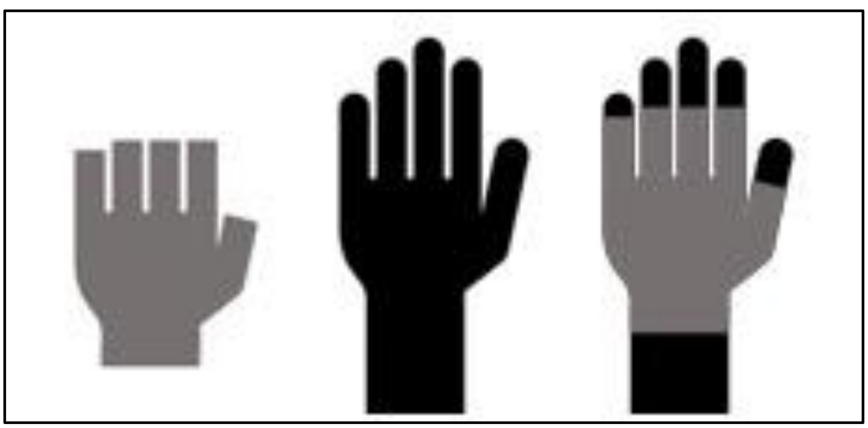


Figure 2.10. Over glove style hoist glove configurations: stand-alone (left), summer flyer flight glove (center), and hoist glove over flight glove system (right).

2.4.2 Flexibility and the Importance of Dexterity

While abrasion resistance for the hoist glove is a crucial component, the ideal hoist glove also must have enough flexibility in the material so as not to hinder the hoist operator's range of motion. During an active helicopter rescue, the hoist operator (also known as a crew chief) has to maintain focus on several tasks while also keeping track of the cable activity. The National Search and Rescue Academy training manual states that the crew chief is responsible for all operations in the cabin of the helicopter. Along with controlling the movement of the hoist cable, the operator also manipulates a pendant that works as the mechanical controls for the hoist and radio transmissions. Aside from working the pendant, the operator also may have to connect or disconnect any number of straps or carabiners as subjects are brought in the aircraft. During rescue operations, several issues can arise with the cable including formation of kinks, tangles, or "birdcaging", which is where the hoist cable stretches open or the outer wire strands unwrap in an uneven manner (Figure 2.11).

Figure 2.11. Zephyr International photograph of hoist cable "birdcaging" and needing immediate replacement [2].

The hoist operator needs dexterity to manually correct these issues if at all possible, all while stabilizing the cable as natural rotation is occurring during the hoist. If the cable becomes tangled beyond recovery during the rescue, they can activate the cable cut button on the pendant, or if there is further malfunction, the hoist operator may need to utilize a manual cable cutter in the event of squib (emergency disconnect mechanism) failure. After the cable is cut manually with the cutter tool, the hoist operator may need to splice the cable if no backup hoist or aircraft is available [1]. In research conducted on rubber and polymer gloves, Irzmanska and Stefko advised that bending rigidity tests were important to monitor in conjunction with durability testing due to the mechanical conditions that users could experience including excessively rigid gloves [34]. Irzmanska also advised that the objective of the study was to eliminate any discomfort and hazards caused by the selected external factors, in their case mineral oils and mechanical factors [34]. This concept aligns with the same general purpose for the rescue hoist glove: provide adequate abrasion resistance to the hoist cable without compromising the user's dexterity. In another study conducted on the effect of certain glove characteristics on the influence of control manipulability, Bradley found that during dexterity tests that their positive correlations between operation time and protectiveness were due to the apparent correlation shown between more supple materials having less protective power generally [35]. Bradley continued on to further extrapolate that the performance of a glove should not have to suffer for the sole reason that the glove is supposed to be protective, and further attributed the decrease in performance had to be from the loss in flexibility in the material [35]. Much like the studies mentioned, hoist glove development requires the best configuration of qualities to achieve the highest abrasion resistance possible while not reducing performance of the end-user.

Research has also been conducted regarding the change in surface friction compared to the thickness of the material, which also could be relevant due to the need of using leather alternatives [36]–[39]. In a study concerned with testing glove stiffness in terms of muscle activation using surface electromyography (SEMG) methodology, Lariviere et. al. point out that gloves used for protection can have an adverse effect on the user's ability to perform tasks, with noticeable changes in performance time, tactility, and range of motion [40]. This compromised performance can also make the user less likely to actually use the gloves all together, putting them further in harm's way [40]. With a glove material that is abrasion resistant but too stiff to allow the free movement required for proper hoist operations, the operator, crew, and rescued subjects could be in danger. The following section discusses the various ways that the glove wearer has implemented to "work around" poor glove design.

2.5 User Wear Considerations

As with any other garment or equipment, though the designers and engineers might have a specific use for the product, and the end user may ultimately manipulate or modify the item in the manner that they choose to achieve their desired preference. There are multiple ways that the responders modified their gloves prior to use, including rolling their gloves at the wrist or cutting off fingers in the over glove to increase dexterity and ease of movement.

Figure 2.12. Responder modified work glove for use in hoist operations, with two fingers and the thumb cut out of the full glove.

Gloves can be modified by users in other ways, some as simple as rolling the gauntlet-style (past the wrist) length protective gloves up towards the heel of the hand in an attempt to gain more flexibility in their hand and wrist motion. This echoes the notion mentioned previously by Lariviere that impaired hand performance and productivity makes the user less likely to use the gloves all together [40]. This can seem like a good option to operators at the time of use, ultimately it places them in danger of injury depending on the circumstances. For example, an injury could occur if the cable catches the roughly cut edges of the glove as seen in Figure 2.12 and jerks the operator's hand into the cable. An ideal rescue hoist glove will combine the abrasion resistance needed for the cable protection, while incorporating a flexibility-minded design that is comfortable and intuitive for the operator. With the operators' needs in mind, the next focus will be on understanding the abrasion caused by the rescue hoist cable.

CHAPTER 3 . REVIEW OF ABRASION TEST METHODS AND APPROACHES

3.1 Introduction

After identifying and understanding the specific application that needs to be replicated, the next step is to develop the approach to a consistent, repeatable procedure. This chapter walks discusses abrasion at the basic level to gauging the methods in terms of real-life application against testing repeatability. Though standardized test methods can easily be used to compare materials data at a glance, application centric reasoning is essential to obtaining data on material behavior and lifespan.

3.1.1 Abrasion Defined

The American Society for Testing and Materials, also known as ASTM International, defines abrasion as “the wearing away of any part of a material by rubbing against another surface” [4]. There are volumes upon volumes of material dedicated to attempting to understand this destructive process. Why is abrasion important? In terms of textiles, the abrasion resistance of a material could determine the lifespan of any material that one can encounter depending on the application. From clothing to the furniture upholstery, to the carpet one walks on, one would be hard-pressed not to notice things “wearing out” over time. There is a distinction between something being “worn out” as opposed to undergoing abrasion; specifically, abrasions are only one component of causes for a material to eventually have yarn breakage leading to visible holes in the fabric (material failure) [5], [6]. However, this research studied the concept of textile abrasion specifically related to the mechanism of a specific abrader and how these observations led to a repeatable testing method that considers both the materials encountering the abrasion, as well as the mechanism causing the abrasion. [6]–[8][9] Mechanisms for the types of abrasion for textiles will be discussed in the subsequent section.

3.1.2 Mechanisms of Abrasion

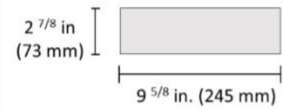
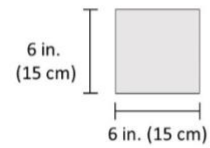
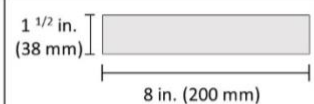
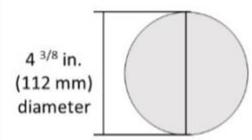
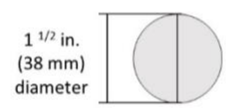
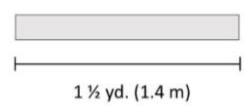
For textiles, there are three basic types of abrasion that can occur on a material which are determined by the relationship between the fibers in the material and the abradant. Any fabric mechanical reaction can be related to three cohesive forces: cohesion between the abrasive agent and the fiber, between fibers that are contiguous, and structural cohesion of the fiber itself [10]. This concept is important because it allows for the prediction of the resistance of textiles to the various types of abrasion based on the geometrical and inherent properties of the fiber, the form factors for the yarn and material sutures, and the forces of friction between the material and abrasive sources [7][11]. The three types of abrasion in terms of textiles are plane abrasion, edge abrasion, and flex abrasion [12]. In the subsequent sections, current standards for these abrasion mechanisms will be explored. Plane abrasion, also known as flat abrasion results from surface rubbing of a material. Edge abrasion results from specific contact of the fabric at the edges of the material. Flex abrasion results from flexing, folding, or bending of a material [13][10][8]. In order to understand how abrasion occurs and attempt to prepare materials for these abrasions, ASTM has made several standard test methods, which will be explored in the next section.

3.2 Test Methods for Evaluating Abrasion Resistance—Investigating Standard and Modified Approaches

Abrasion testing is not a new idea in the field of textiles. Currently, many of the abrasion tests were first implemented in the mid-twentieth century and are very application specific [14][7]. A comparison between the various abrasion test methods is necessary to achieve desired results without unintentionally duplicating techniques. Abrasion resistance can be related to the durability, normally quantified by amount of repetitions of the test method to the designated end point, whether that be to a certain predetermined endpoint (ex. material failure/hole in the fabric) or abrading to a set number of cycles/repetitions/iterations before evaluation [7], [8], [12],

[14][15][16]. With an understanding of abrasion test methods, the facet needing examination is the apparatus doing the abrading. The mechanism of these abrasion systems relies on friction; whether it is between the textile and other materials, an external object, particulate matter (dust/grit), or fabric components (ex. stitching, material slippage) [14][17][18]. The differences in mechanism for abrasion systems are to simulate different end-uses, which can be modified by type of abradant used, amount of pressure applied, and size of the abraded area [19]. ASTM provides a standardized set of testing methods compiled in one book/publication for use and reference for a variety of techniques. A quick reference of common ASTM test methods for abrasion testing of textiles can be seen in Table 3.1. The purpose of this review is to examine existing abrasion testing methods in order to understand the similarities and differences between the processes. Information has been grouped according to ASTM test method, with a focus on relevant standard test methods outlined in terms of apparatus/procedure, variables tested, range of applications, maintenance, and abrasive mechanism. The first four standard testing methods are tested on everyday materials like household fabrics, industrial fabrics, and floor coverings with either woven, non-woven, or knit construction.

Table 3.1. Reference chart for common ASTM standard test methods used for evaluating textile abrasion resistance.

ASTM Standard #	Apparatus	Material Tested	# of specimens	Sample Shape
D4157	Oscillatory Cylinder (Wyzenbeek)	Household fabrics, industrial fabrics, floor coverings; woven, non-woven, knit	**12 total (6 in warp direction, 6 in fill direction)**	 2 7/8 in (73 mm); 9 5/8 in. (245 mm)
D3884	Rotary Platform, Double Head (Taber)	Household fabrics, industrial fabrics, floor coverings; woven, non-woven, knit	**5 total**	 6 in. (15 cm); 6 in. (15 cm)
D3885	Flexing and Abrasion Tester	Woven and nonwoven fabrics without excessive stretch (floor coverings not suitable)	**8 total (4 in warp direction, 4 in fill direction)**	 1 1/2 in. (38 mm); 8 in. (200 mm)
D3886	Inflated Diaphragm Tester	Household fabrics, industrial fabrics, floor coverings; woven, non-woven, knit	**5 total**	 4 3/8 in. (112 mm) diameter
D4966	Martindale Abrasion Tester	Household fabrics, industrial fabrics, floor coverings; woven, non-woven, knit	**3 total**	 1 1/2 in. (38 mm) diameter
D6770	Webbing Abrasion Tester (Hex Bar)	Automotive, aerospace, industrial, military applications	**2 total**	 1 ½ yd. (1.4 m)

3.2.1 ASTM D4157– Oscillatory Cylinder Method

This testing method determines the abrasion resistance of woven textile fabrics using the oscillatory cylinder (Wyzenbeek abrasion tester, Figure 3.1) [20].

Figure 3.1. Wyzenbeek abrasion testing apparatus, side view.

Testing Apparatus

The Oscillatory Cylinder Abrasion Tester, or Wyzenbeek machine, is comprised of an oscillating cylinder equipped with clamps for mounting, four specimen holding arms, two different calibrated masses, thumb screw, sponge rubber pressure pad, two slotted vacuum pipes, and an automatic cycle counter (Figure 3.1) [6]. The abradant sheet placed on the apparatus can be a cotton material, a two-piece laminated stainless steel wire mesh screen assembly, or grit sandpaper (which can also be used to refurbish the rubber pads). The most common head pressure used is 13.4 Newton (N) or 3 pounds of force (lbf) with 17.8 N or 4 lbf specimen tension, which would work for general to heavy duty upholstery end uses, but would not be suited for extremely abrasion resistant materials due to the time and energy needed to make any worthwhile abrasions; the caveat is that there would be little, if none at all, abrasions visible due to the relative low pressure on the material and abrasive aggressiveness of the available abradants for more abrasion resistant materials.

Abrasive Mechanism

The abrasion occurs at the contact point where the sample is held taut in place while the specific abradant sheet fixed to the oscillating cylinder rubs back and forth. Abrasion intensity can be adjusted using sample tension, head weight, or abradant screen choice. Visually, abrasion shows as a linear area across the width of the material in the center of the sample, which can be seen in Figure 3.2.

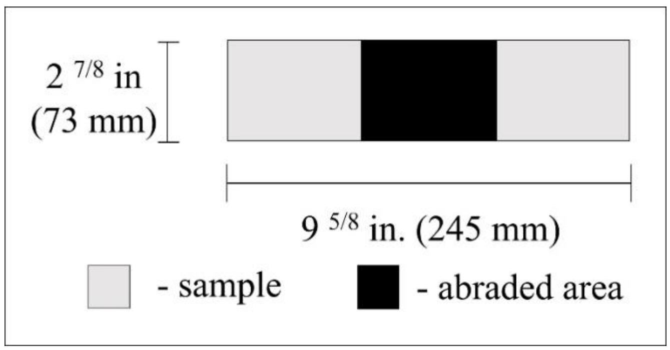


Figure 3.2. Abraded area for samples tested with Wyzenbeek abrasion tester.

Testing Procedure

Twelve specimens are cut in 2 7/8 in (73 mm) by 9 5/8 in (245 mm) rectangles (six in the warp direction, six in the fill direction), and then conditioned in standard atmosphere for testing textiles (70 ± 2° F or 21± 1 °C, and 65 ± 2% relative humidity), as seen in Table 3.1. The test method evaluates abrasion resistance by applying unidirectional rubbing to the specimen under predetermined conditions of pressure, tension, and abrasive action. After the abradant is selected, specimens are mounted, tension is set as the sample is pulled taut, and the number of cycles is set to either a specified number or 3000 as specified by the standard test method and testing preferences for the material.

Testing Variables

A cycle is one motion back and forth against the sample, which is also called a "double rub". The results are gathered in terms of abrasion to rupture ratio, percentage loss in breaking load, evaluation for visual changes in terms of either broken yarns/appearance of a hole or color change. Reporting the results depends on the test options used, the abradant used, tension, and load adjustment.

Apparatus Maintenance

Rubber pads should be changed at least once per year, while the cylinder section, steel screen, and vacuum system should be cleaned once per week. Calibration includes checking the tension with a digital force gauge, repositioning the bars as needed.

3.2.2 ASTM D3884 - Rotary Platform, Double Head Method

This testing method determines the abrasion resistance of textile fabrics using a rotary platform, double head (RPDH) tester, also known as the Taber® abraser (Figure 3.3) [4].

Figure 3.3. Taber® abrasion testing apparatus.

Testing Apparatus

The rotary platform, or most commonly the Taber® abraser (Figure 3.3) is comprised of a removable turntable platform with a rubber pad, clamp plate and knurled nut, and clamp ring to secure the specimen; pivoted arms that attach to the abrasive wheels and weights, platform rotating motor, vacuum nozzle and cleaner for debris removal, and revolution counter [8]. Abrasion setup involves using specialized abradant wheels, Calibrade® Taber® abrading wheels, with a specified weight up to 1000 grams. Calibrade® is composed of a non-resilient, vitrified binder and aluminum oxide or silicon carbide abrasive particles. Abradant wheels vary in abrasive texture, with applications ranging from abrading delicate textile fabrics to heavy duty automotive carpet materials. While the abradant wheels are more aggressive than the abradant fixed to the oscillating drum of the Wyzenbeek mentioned previously, the abrasive conditions for the Taber® are circular, relatively flat. Taber® Industries also manufactures some modifications on their original rotary platform design, one of relevance being the "linear abraser". The Taber® linear abraser utilizes a free-floating head to follow the surface shape (flat, convex, or concave), and an adjustable stroke length of 0.2 inches to 4.0 inches with load weights up to 4050 grams [13]. Even so, this abrasion is only over a small area with the abrasions occurring in terms of inches per minute.

Abrasive Mechanism

For this testing method, the abrasion occurs at the contact points where the two abradant wheels roll across the face of the sample as the platform rotates. Abrasion intensity can be adjusted by changing the abradant wheel type, accessory weight, or counterweight. Visually, abrasions show in a circular pattern relative to the rectangular sample shape, with the diameter of the circle being the same width as the Calibrade® wheels are set apart (Figure 3.4).

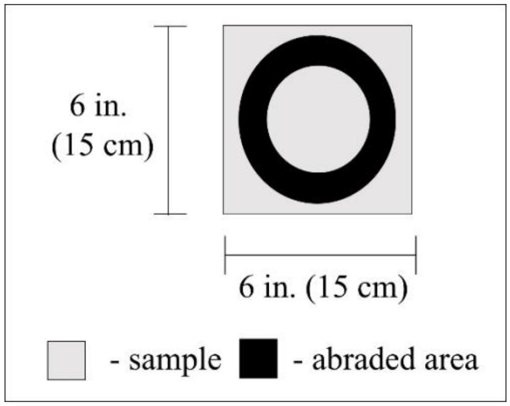


Figure 3.4. Abraded area for samples tested with Taber® abraser.

Testing Procedure

Five specimens are cut in to approximately 6 in (15 cm) squares, then conditioned in standard atmosphere for testing textiles (70 ± 2°F or 21± 1 ºC, and 65 ± 2% relative humidity) (Table 3.1). Special care needs to be taken in avoiding any surface anomalies, such as folds, wrinkles, creases, oils, or water since contamination can alter the abrasive properties of the wheels or the material. After the specimens are mounted in the specimen holder, the abrading heads and vacuum head are lowered carefully onto the specimen, and then when turned on, the abrader runs for the specified number of cycles.

Testing Variables

The results are gathered in terms of residual breaking force (tested with separate tensile testing apparatus), average breaking strength, percent loss in breaking strength, and cycles to a specific end point. Reporting the results involves specifying the type of abradant wheel used, the load adjustment/counterweight, vacuum suction level, height of vacuum nozzle, along with the results obtained depending on the information attained. Another standard test method that also applies to the Taber® abraser is ASTM D4060 (Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber® Abraser), but would not be applicable in this case due the focus being on textiles [8].

Apparatus Maintenance

Care should be taken concerning equal spacing of the wheels, alignment of wheel bearings, proper platform positioning (no visible wobble), correct platform speed (72 ± 2 rotations per minute), good vacuum suction, and preparing the resilient abrading wheels for calibration. Resurfacing disks should be used prior to each new specimen, using 25 or 50 cycles depending on the duration of the previous specimen abrasion.

3.2.3 ASTM D3886 - Inflated Diaphragm Apparatus

This testing method determines the resistance to abrasion of woven or knitted textile fabrics, both conditioned and wet, using the, Inflated Diaphragm Abrasion Tester (Figure 3.5) [21].

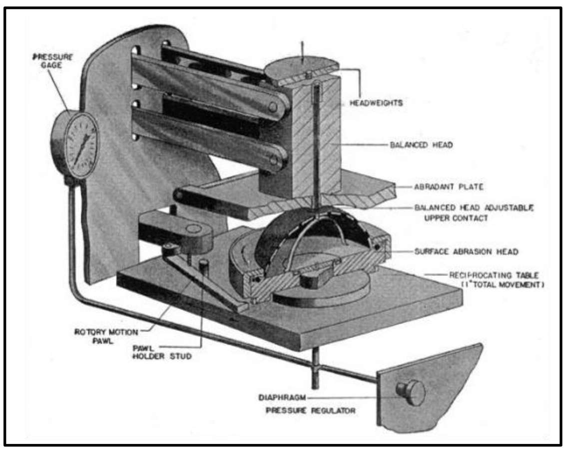


Figure 3.5. Inflated Diaphragm Abrasion Tester diagram [19].

Testing Apparatus

The Inflated Diaphragm Abrasion Tester is comprised of a surface abrasion head, diaphragm, driving mechanism, balance head and abradant plate, stopping mechanism, and indicators [10]. Abradants used can be paper or other abrasive materials, which can be placed on a continuous changing abradant head or a static head, with air pressure set in the diaphragm to be 4 psi (28 kPa) with the load on the abradant set at 1 pound (454 grams).

Abrasive Mechanism

Abrasion occurs at the center of the sample mounted over the inflated diaphragm where the abradant rubs across back and forth. The abrasion direction can also be specified, with the ability to choose between standard multi-directional or uni-directional patterns depending on the engagement of the rotation mechanism. Visually, abrasions show in the center of the sample at the apex of the inflated area, in a linear pattern relative to the direction of the back and forth motion of the abradant.

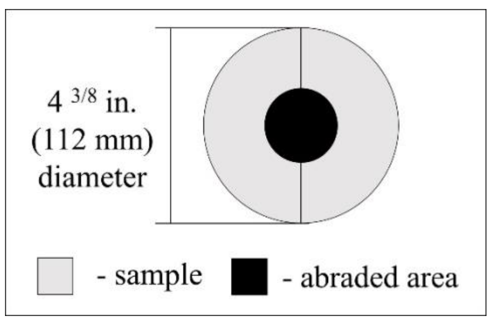


Figure 3.6. Abraded area for samples tested with inflated diaphragm abrasion tester.

Testing Procedure

Five specimens are cut in 4 3/8 in (112 mm) diameter circles and are conditioned in standard atmosphere for testing textiles (70 ± 2°F or 21± 1 ºC, and 65 ± 2% relative humidity) (Table 3.1). After the specimens are placed over the rubber diaphragm and clamped down, the abradant is placed on top and secured, and the air pressure and force are set on the abradant plate. The direction of abrasion is chosen, then carried out, removing matted fibers that interfere with contact between the specimen and abradant as needed.

Testing Variables

Results are taken by pre-specified endpoint, which can be abrading material to failure, or abrading to a specific number of cycles and visually rating on a 1-5 scale. On the scale, 1 is a severe change in color with two or more broken threads and a 5 is essentially no change. For reporting, the abradant type must be specified, along with the abradant paper change frequency, air pressure and load on abradant plate, abrasion direction, cycles to endpoint or effect on visual properties, and any deviations from the standard test procedure.

Apparatus Maintenance

Calibration for the apparatus is more concerned with uniform inflation of the diaphragm in the sphere shape and driving mechanism of around 115 double strokes per minute [10]. This rate also rules out being comparable to the feet per minute of the hoist cable and would require an excessive amount of time and cycles completed, if able to show abrasion at all.

3.2.4 ASTM D4966 - Martindale Abrasion Tester Method

This method determines the abrasion resistance of all types of textiles fabrics with a pile depth of greater than 0.08 in (2 mm) by the Martindale abrasion tester (Figure 3.7) [22]. The Martindale is the most common method of testing abrasion resistance of textiles.

Figure 3.7. Martindale abrasion testing apparatus.

Testing Apparatus

The Martindale Abrasion Tester is comprised of standard abradant fabric and felt, polyurethane foam backing, fabric punches, and the machine to place the specimens. Issues other than surface abrasion are more likely to end in failure of the material, so material conditions also need to be considered. The assembled specimen holder on the machine should be set depending on the type of material being abraded, with apparel fabrics set to 1.31 ± 0.3 psi (9± 0.2 kPa) or for upholstery fabrics 1.74 ± 0.04 psi (12 ± 0.3 kPa), and a mounting weight of at least 2.5 ± 0.5 kg . The Martindale abrasion testing apparatus can be seen in Figure 3.7.

Abrasive Mechanism

Abrasion occurs at the interface of the sample and abradant material, with the sample being rubbed across the abradant face in a geometric pattern. Abrasion intensity can be adjusted by changing the abradant material type that the sample is rubbed across. Visually, the abrasions appear near the center of the sample, wearing in holes rather than in a linear pattern, usually at the center of the sample, which can be seen in Figure 3.8.

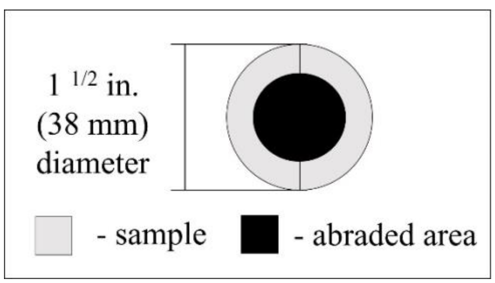


Figure 3.8. Abraded area for samples tested with Martindale abrasion tester.

Testing Procedure

Three circular specimens are cut from each sample being tested, with a 1.5 in (38 mm) diameter, and then are conditioned in standard atmosphere for testing textiles (70 ± 2°F or 21± 1 ºC, and 65 ± 2% relative humidity) (Table 3.1). The specimens are placed in between a metal insert and a polyurethane foam disk, then placed into assembled holders in the machine, before setting the counter and adding weight prior to turning machine on.

Testing Variables

Results are gathered in terms of either broken yarns/fabric hole or a change in shade being observed on the surface of the fabric. Reporting involves specifying the type of abradant, either the average number of rubs to failure or effect on physical qualities, and mass loss. Assessment of the abraded material includes examination at pre-specified intervals depending on the fabric characteristics, looking at broken threads, mass loss, or appearance changes [22].

Apparatus Maintenance

The abradant fabric should be changed for every new specimen, as well as at 50,000 rubs if fabric breakdown had not occurred at that point. The Martindale abrader is only strong enough to handle upholstery, so highly abrasion resistant materials would not be abraded as desired. Also, the rate and aggressiveness of the abrasion for the Martindale would require several changes of the abradant fabric and would give a circular wear.

3.2.5 ASTM D3885 - Flexing and Abrasion Method

This testing method determines the abrasion resistance of woven or nonwoven textile fabrics by the flexing and abrasion tester (Figure 3.9) [23]. While not suitable for floor coverings, this testing method looks at abrasion resistance of stiffer materials, like leathers or materials without a lot of stretch by pulling them back and forth across the abradant until the material fails.

Figure 3.9. Flexing and Abrasion Tester in the Wilson College of Textiles' Physical Testing Laboratory at NC State University.

Testing Apparatus

The Flexing & Abrasion Tester is comprised of a balanced head and flex block assembly with two parallel plates connected with clamps, flexing bar yoke, thumb screw, micro switch stopping mechanism, cycle counter, two flex bars, calibration ribbon, and calibrated weights for tension and head weight [9]. Tension head weights are usually around 4 pounds, whereas the head weights are usually satisfactory around one pound. The Flexing and Abrasion Tester can be seen in Figure 3.9.

Abrasive Mechanism

The abrasion mechanism takes place at the working flex bar, which has one edge for abrading, and the other portions polished smooth. The abrasion occurs at the edge of the sharpened edge of the steel hexagonal rod, which is otherwise polished down smoothly; the sample is pulled back and forth across the rod. Abrasion intensity is normally chosen ahead of time due to the breaking strength of the material determining what type of mass to use; for webbing with breaking strength of up to 1000 lb. (4500 N) a mass of 2 lb. ± 2 oz (900 ± 60 grams) should be used, 4 lb. ± 2 oz (1800 ± 60 g) for breaking strength of 1000 to 3000 lb. (4500 to 13,500 N.), and 5.2 lb. ± 2 oz (2400 ± 60 g) for breaking strengths over 3000 lb. (13,500 N). A diagram of the area abraded using the Flexing and Abrasion tester can be seen in Figure 3.10.

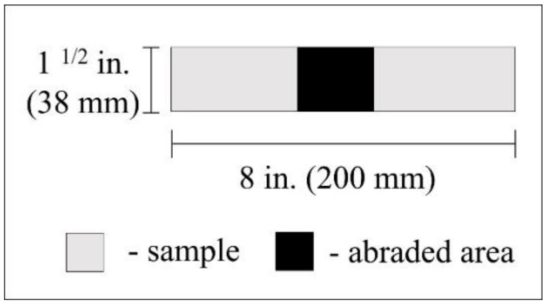


Figure 3.10. Abraded area for samples tested with Flexing and Abrasion tester.

Testing Procedure

This test method is not applicable for materials that stretch excessively or floor coverings. Samples are cut into four warp and four fill directions specimens at least 200 mm (8 in) long and between 1 ¼ in (32 mm) and 1 ½ in (38 mm) wide depending on the number of yarns per 25 mm (Table 3.1). The specimens are then conditioned in standard atmosphere for testing textiles (70 ± 2°F or 21± 1 ºC, and 65 ± 2% relative humidity). After the specimen is clamped in and threaded through the flexing and abrasion apparatus, the head is released, and tension is applied before releasing the yoke is released and the counter is set before letting the machine pull back and forth.

Testing Variables

Results are gathered in terms of average cycles to rupture, average breaking strength of both abraded specimens and specimens not abraded, percentage loss in breaking strength, along with the standard deviation of breaking strength percentage and coefficient of variation. Reporting involves relaying those gathered parameters for both the lengthwise and widthwise specimens, as well as the manufacturer and model of the test instrument.

Apparatus Maintenance

Calibration is performed with special ribbon made of fused acetate, about 1 inch wide, provided by the abrader manufacturer, placed on the apparatus in the same way as a specimen. Visually, the abrasions show as imperfections or broken yarns at the center of the sample nearest to the flex point. Calibration wise the test machine needs to be on a vibration free, level surface, and the hexagonal rods need to be maintained, kept free of any imperfections, with a cold drawn finish and a Rockwell Hardness of B-91 or B-101.

3.2.6 ASTM D6770 - Hex Bar Method

This testing method determines the abrasion resistance using a hex bar abrasion tester for textile webbing (Figure 3.11) [24]. This method is similar to the flexing and abrasion tester in terms of concept, but the tested material is far more rugged. Generally tough materials used for automotive or industrial applications are specifically selected for this test.

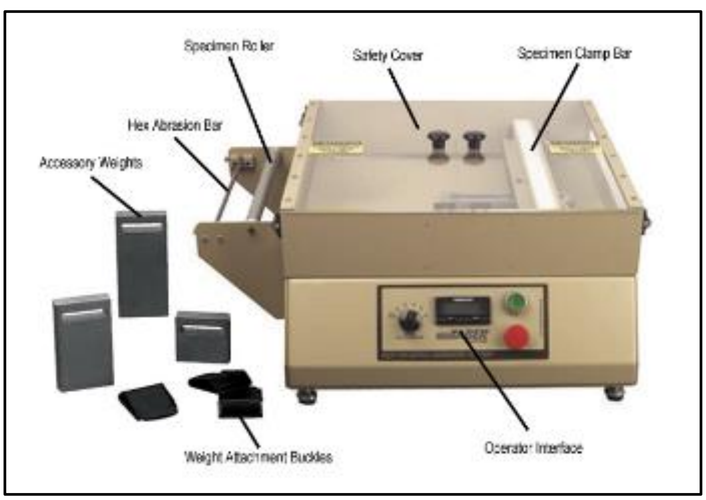


Figure 3.11. Webbing Abrasion Tester with hex bar [24].

Testing Apparatus

The hex-bar abrasion tester, or Webbing abrasion tester, is comprised of a standard hex bar attached to a machine capable of reciprocating motion with the sample. The sample is attached to the reciprocating mechanism at both ends, with the center passing across the hex bar and tension set. A drum moves the specimen across the hex bar and can have weights attached, which can be seen in Figure 3.11.

Abrasive Mechanism

Abrasion occurs at the point where the sample rubs back and forth while being pulled across the hexagonal steel rod. Abrasion intensity can be adjusted by changing accessory weights/buckles. Visually, abrasions show at the center of the sample length, near the hex bar area. The Hex Bar abrasion tester is comprised of a mechanism for reciprocating motion of the webbing over a fixed, standardized hex bar [12]. One specialized type of hex bar tester can be seen in Figure 3.11, which is used for testing the abrasion resistance of seatbelt straps. The Webbing abrasion tester shows abrasions in the middle section of the sample, around twelve inches across the entire width of the material (Figure 3.12).

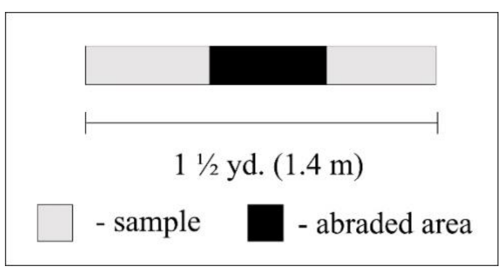


Figure 3.12. Abraded area for samples tested with Webbing abrasion tester.

Testing Procedure

Two specimens are cut to 1.4 meters (1.5 yard) in length, one marked "A" for abraded and the other marked "U" for unabraded before being conditioned in standard atmosphere for testing textiles (70 ± 2 ºF or 21± 1 ºC, and 65 ± 2% relative humidity) (Table 3.1). The specimens are mounted with the required mass attached to a drum, then oscillate across a hexagon rod across around 300 mm (12 in) at the rate of around one stroke per second for 5000 strokes.

Testing Variables

Results are gathered in terms of average breaking force for both the abraded and unabraded specimens, as well as the retained breaking force to the nearest one percent, which is then placed in the report. Also, the specimens evaluated are longer in length, like a seatbelt strap, and would not be representative of the smaller surface area exposed to the longer linear abradant.

Apparatus Maintenance

The hexagonal rods need to be recertified if any burrs, nicks, or scales form. The surface where the apparatus is located must also be free from vibrations as that can alter the results.

3.2.7 Modified Abrasion Test Methods

Understanding the mechanism of textile abrasion is essential in choosing a testing technique that correctly represents the conditions encountered by the material, while also allowing for repeatable testing results in order to obtain meaningful data. Standardized tests such as the ASTM abrasion test methods provide a methodological framework of aspects to consider while evaluating materials, though using those standards might not always be the best option in evaluating a material due to the great differences between the standardized test method conditions and actual applicable conditions [25], [26]. In these unique cases, a modified version of standard test methods could be used, or a completely new method could be developed with respect to those specific conditions incurred. This section will examine three instances of new test methods being implemented for more realistic reporting of material degradation.

One set of researchers modified standard testing methods to compensate for the differences in abrasion resistance of leather motorcycle protective clothing in laboratory testing and data from actual motorcycle crashes [27]. Bolschweiler was concerned with finding a reliable method to examine materials used to produce motorcycle protective clothing after noticing discrepancies between the values for abrasion resistance found using the Taber® data compared to the actual conditions experienced during motorcycle crashes. The data for abrasion resistance of the materials tested were found in other research using the Taber® abraser, which did not provide an accurate representation of the types of abrasion actually experienced during motorcycle crashes. After development, Bolschweiler discovered that using a lawn edge stone to produce the abrasions provided a much more accurate representation in terms of visual comparison and reported cycles to failure, though the direction of the abrasion was circular instead of linear due to the machine used. The alignment of accurate abrasion mechanism representation and repeatable testing method provided valuable information in terms of actual material behavior for the leather motorcycle protective clothing, resulting in the development of better protective clothing in the future.

Another set of researchers modified a standard abrasion testing apparatus in order to accurately represent the abrasive conditions experienced in a vehicle transmission system [18]. In 1993, Buckley explored various options to try to find a more suitable method to show abrasion incurred for transmission fabrics than standardized test methods. A new instrument was made to mimic the abrasive action seen by a transmission belt drive, with specific focus on providing visually similar abrasions for the materials. The simulated transmission belt drive set up provided a material failure point time that was much closer to the time observed in the engine as opposed to using other standard testing methods just for a trivial data benchmark.

An additional alternative testing method involves simulating the abrasive action between layers of material and a nonwoven interlining [10]. Instead of using subjective measurements for material hand which was standard in the industry at the time, Kalebek used a proprietary apparatus in combination with the standardized test method for the Martindale abrader to test both the frictional behavior and the abrasion resistance. Using the proprietary apparatus allowed material properties to be seen that would have otherwise not been apparent with the subjective measurements or the Martindale abrader alone.

Lastly in a study on the abrasion resistance of socks and hosiery, Gupta challenged the available abrasion testing techniques, concluding that while one could use a Taber® abraser to abrade the hosiery, the effect would not mimic actual wear [28]. Abrasion occurs in hosiery between layers of material, which was not accurately represented by the coarse abrasive Calibrade ™ wheels of the Taber® abraser. Utilizing new ideas and techniques in combination with the test standard methodology allows creative exploration of solutions for the accurate representation of real-world abrasive conditions.

3.2.8 Understanding the Testing Approach—Standard versus Modified

While all six of the ASTM standard test methods are concerned with capturing the abrasion resistance of a material, the approach taken for each is slightly different. In terms of sample shape, the Wyzenbeek, the flexing and abrasion, and the hex-bar all have rectangular samples with the abrasions occurring across the center laterally. The inflated diaphragm and

Martindale both require circular sample shapes, though the sample and abradant motion for each are in opposition. The Taber® is the only square shape, despite the mounting similarity of the inflated diaphragm tester. Several are concerned with statistical analysis of the results to understand the material strength after abrasion, whereas others are only concerned with the amount of abrasions that the material can take before it fails, either by the breaking of yarns or a complete hole in the material. In the standard test method for Taber® abrasion, ASTM mentions that "while 'abrasion resistance' (often stated in terms of the number of abrasion cycles) and 'durability' are frequently related, the relationship varies with different end uses and different factors may be necessary in any calculation of predicted durability from specific abrasion data" [4]. An important notion emerges from these experiences: testing without consideration for conditions experienced could only produce data for the sake of producing data—potentially providing a numerical benchmark for the material behavior, but not anything that would show how the material would react in a real-world situation. Alternatively, combining a representative scenario with a repeatable method can provide information about a material that could lead to better informed design decisions and products overall.

The purpose of this review was to examine existing abrasion testing methods to understand the similarities and differences between processes, as well as the strengths and weaknesses of each technique. The most prominent difference between all these testing methods is the mechanism of abrasion, each having a relatively practical inspiration that was converted into a replicable method to relate application and use.

Advancing technology and newer material resources will continue to provide new situations and conditions that should be considered during textile production and evaluation. Understanding the specific abrasive mechanisms and applying those principles are invaluable when developing protective textiles. The conscious link of the simulated abrasive mechanism with real conditions will provide data that is useful for application/end-use going beyond theoretical application.

3.3 Cable Abrader Apparatus Overview

The cable abrader is a newly developed testing apparatus that utilizes stainless-steel cable rope and brake tension to simulate the abrasive conditions created by a helicopter rescue hoist cable. The cable abrader is comprised of three main components: the simulated helicopter hoist system, the adjustable sample mount, and the attached monitoring software. Abrasion occurs when the sample mount is pressed to the tensioned hoist cable while it moves across the surface of the sample.

In terms of size, this first iteration cable abrader would not be considered a 'bench top' testing apparatus due to the amount of floor space required compared to other abrasion testing machines. The cable abrader has a variable speed control dial and a manual drive system that must be changed to switch back and forth between the gears for "Cable Up" or "Cable Down". Tension on the sample via the cable is monitored via pressure sensors in the sample mount that work with formulas in the software from the load cell outputs. The amount of useable wire rope length on the cable abrader is approximately 250 feet, which is similar to that of an actual helicopter hoist system [41]. The cable speed can run between 10 feet per minute minimum and 140 feet per minute maximum for the cable abrader. Figure 3.13 shows a diagram of the cable abrader apparatus from the side view, with the stainless-steel cable wire rope wrapped around the reel, passing over wheels before going over the sample mount, through another set of wheels and onto the other cable reel. In Figure 3.14, a closer view is seen of the sample holder against the cable at tension, as is illustrated by the bowing of the cable. This unique configuration along with the stainless-steel wire rope cable abradant produces a distinct concentrated linear pattern on the sample tested and provides potential for realistically mimicking the abrasive conditions incurred by a rescue helicopter hoist cable. With a developed testing method using the cable abrader, results could represent the real-life conditions experienced and allow for appropriate application-based material comparisons.

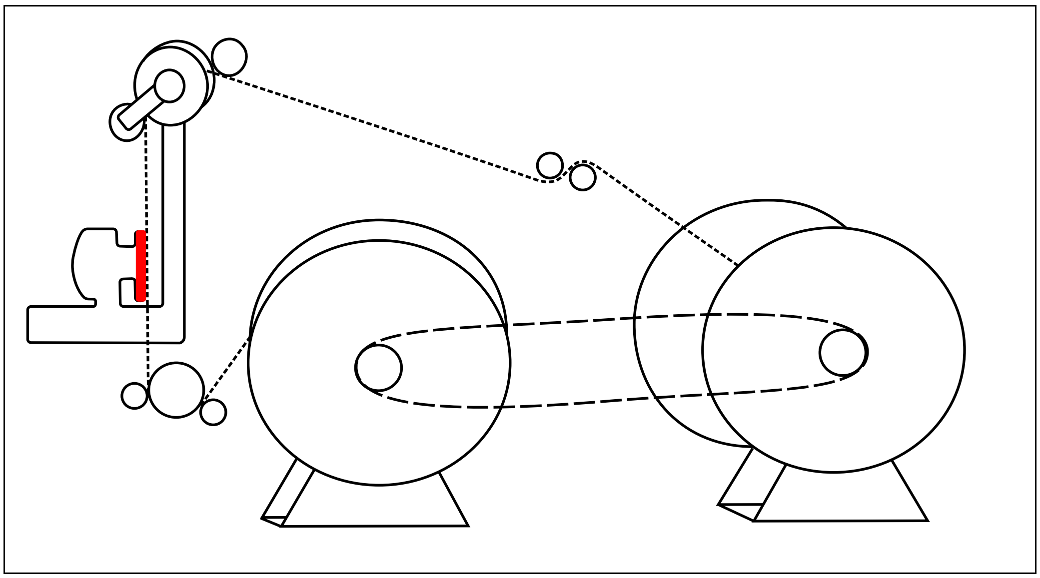


Figure 3.13. Cable abrader diagram side view: cable reels, gear cable, and sample mount (shown red).

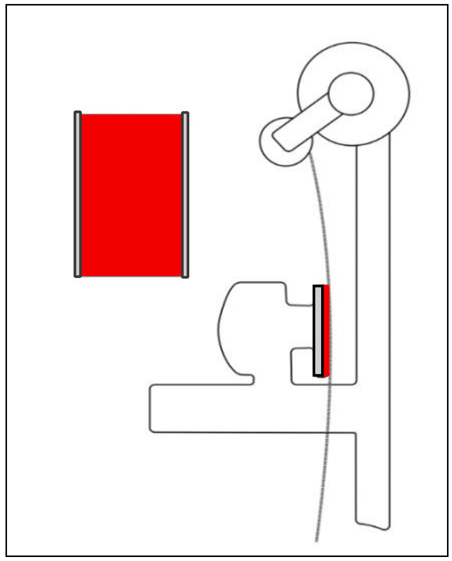


Figure 3.14. Sample mount (shown in red) detail diagram: left showing face of sample mount, and right showing sample mount on cable at tension.

3.4 SuperFabric™

SuperFabric™ is a material manufactured by Higher Dimension Materials (HDM of Minneapolis, MN). SuperFabric™ is highly durable and abrasion resistant with many different applications from sport apparel to industrial automotive components. The material is composed of a fabric that is overlaid with tiny dots (also known as the "guard plate") which can come in various thicknesses and geometries for different applications. The SuperFabric™ guard plate works by providing protection to the surface of the material via the hard dots, while still allowing material flexibility since the dots move along with the fabric. Figure 3.15 shows the side view of the SuperFabric™ material's flexibility in the diagram, with the dots not stifling material flexibility.

Figure 3.15. SuperFabric™ side view showing material flexibility and protective coverage by the guard plate [48].

SuperFabric™ materials have a unique combination of properties including resistance to abrasion and moisture while maintaining flexibility that provides an opportunity in terms of rescue hoist glove design from a material level that leather materials cannot provide.

CHAPTER 4 . LINEAR CONCENTRATED ABRASION TEST METHOD DEVELOPMET WITH CABLE ABRADER APPARATUS

4.1 Introduction and Background

The cable abrader is a new abrasion testing apparatus developed to mimic the abrasive conditions produced by helicopter rescue operations on a hoist operator's protective glove. Currently there is no other abrasion testing machine capable of accurately representing the linear concentrated abrasion pattern caused by the stainless-steel cable rope of the helicopter hoist. An understanding of the real-life abrasive conditions is essential to providing useful results in terms of realistic material longevity and behavior. Consequently, assessing rescue hoist glove abrasion resistance requires an understanding of the abrasive interaction between the protective glove and the hoist cable. The chosen method needs to simulate the specific abrasive action incurred from a hoist glove being pressed against an actively moving helicopter hoist cable back and forth. To accurately represent the abrasive mechanism, the technique must have an appropriate abrasion pattern, intensity, and concentration. Part of developing the test method for the cable abrader studied well defined ASTM abrasion test standard methods to see what components of each would be useful and applicable. From there, the different sources of data needed to be explored for relevancy, and running conditions needed to be optimized. With those conditions met, a well-rounded testing approach can be attained for using the cable abrader.

4.1.1 Cable Abrader Apparatus

The cable abrader is comprised of a set of reels holding around 275 feet of stainless-steel cable rope, mechanically controlled by a brake system and monitored with on-board software. The useable cable length is approximately 250 feet with the remainder of the cable rope wrapped between the two reels to ensure proper cable tension without causing damage to the cable. The stainless-steel cable is 3/16 inches (4.76 mm) thick, with an inner core wrapped clockwise and the outer threads wound counterclockwise. The sample is attached to the sample holder which is connected to the sample mount, and can be adjusted using one of two rail actuators; one actuator rail moves the sample towards or away from the cable, and the other actuator rail moves the sample mount between two set stops on either side of the cable to compensate for the rolling motion the cable undergoes due to the construction of the wire rope. Several components of the cable abrader are fully adjustable, including the speed dial and brake tension. Switches are also employed for other modes needing adjustment, active options including the power switch (on/off modes), the brake power switch (on/off modes), the brake selection (cable up/neutral/cable down modes), with an inactive mode for water control for future machine iterations. The image in Figure 4.1shows the cable abrader apparatus with the sample mount area enclosed, as it would be during the actual cable run portion of sample processing. The main components of the cable abrader can also be seen in Figure 4.1, with the laptop computer sitting on top of the protective case for the apparatus, the sample mount and load cell visible inside the front of the enclosed area, and the cable reels and brake gears in the center of the apparatus.

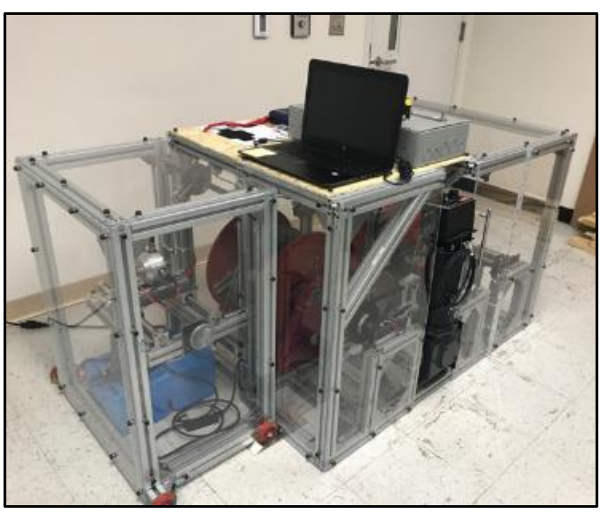


Figure 4.1. Cable abrader apparatus with sample mount area enclosed

4.1.1.1 Simulated Helicopter Hoist System

To mimic the conditions incurred by the helicopter hoist cable an identical cable has been mounted in the bidirectional reel system. The cable is 3/16-inch stainless steel wire rope, with a usable length of approximately 250 feet. Cable length on the cable abrader is comparable to that used in actual helicopter hoists, with common rescue helicopters using cable between 200 and 250 feet long [42]. An adjustable set of brake and speed controls set the cable speed, with a speed setting of 6 generally showing to be around 93-98 feet per minute average over the course of a cable run. The brake system is manually switched between gears, with the active direction having the desired gear locked in (Figure 4.2).

Figure 4.2. Cable Abrader manual gear shown from the top, with gear for "Cable Down" selected.

The cable runs between two reels through a series of wheels to help keep tension, each direction run serving as a simulation for either cable being deployed or retracted into the hoist. Figure 4.3 shows the “Cable Up” configuration, with the cable passing from the front reel through a series of wheels before passing upwards over the sample mount to mimic the helicopter hoist cable retracting into the hoist drum. Figure 4.3 shows the “Cable Down” configuration, with the cable passing from the back reel through a set of wheels then down vertically across the sample mount to mimic the helicopter hoist cable deploying down to the scene.

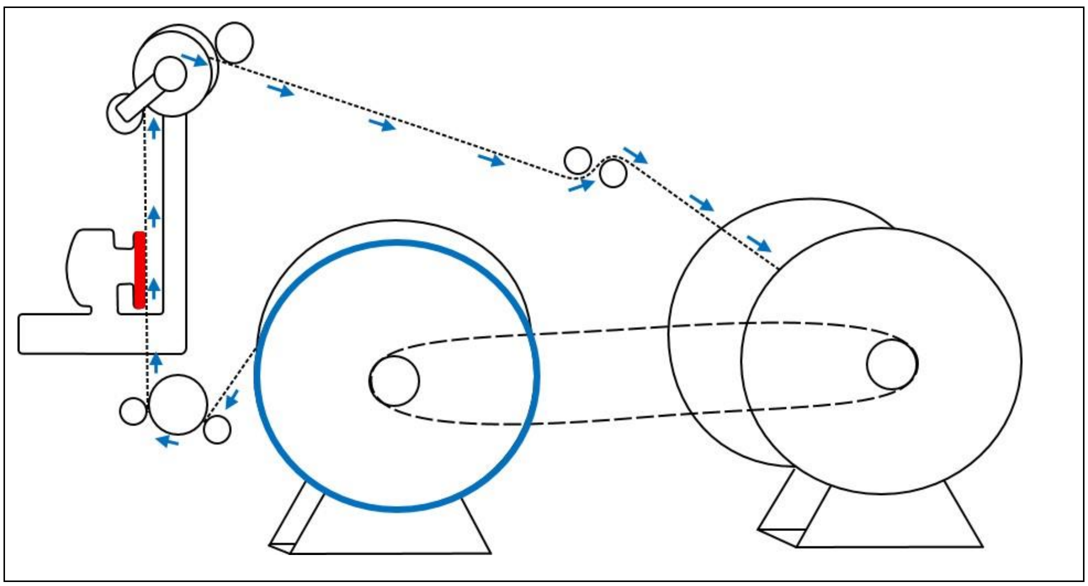


Figure 4.3. Cable abrader diagram, “Cable Up” configuration, front reel loaded with cable, cable direction passing up vertically across the sample mount and wrapping around the back reel.

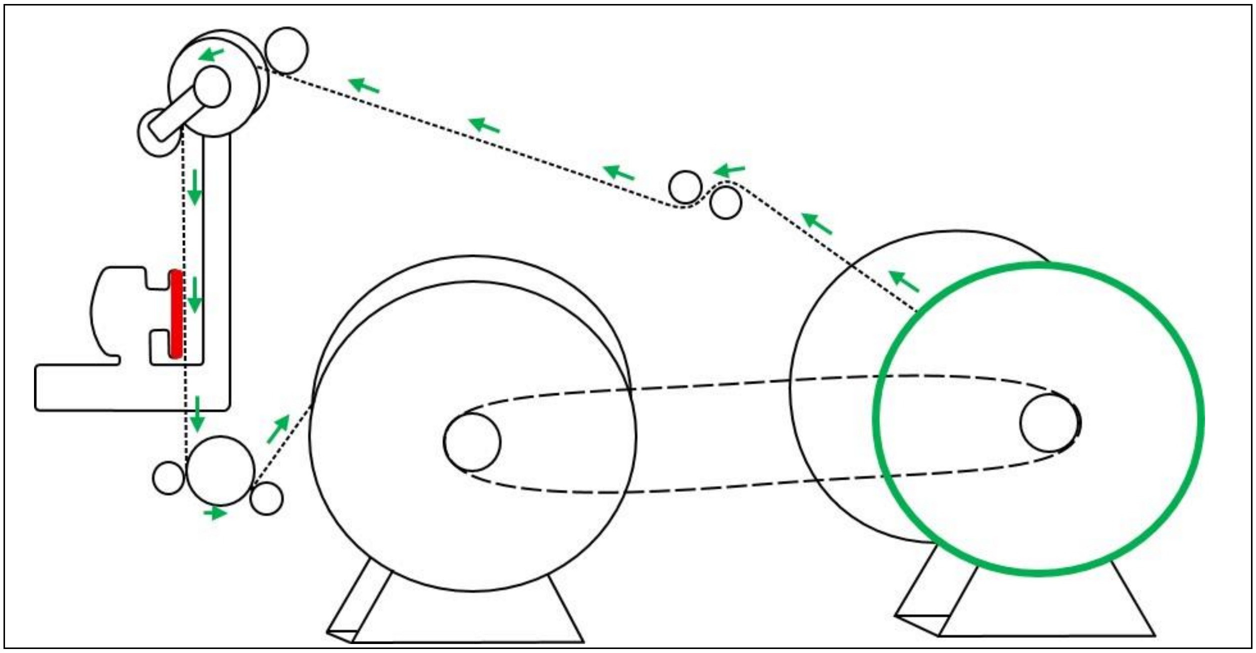


Figure 4.4. Cable abrader diagram, “Cable Down” configuration, back reel loaded with cable, cable direction passing down vertically across the sample mount and wrapping around the front reel.

4.1.1.2 Sample Mount

The sample mount is connected to the load cell and can be pushed into the cable at tension to mimic the force of a hoist glove being worn and pushing against a helicopter hoist cable by the operator. The side view of the sample mount can be seen in, where the white arrow shows the trajectory of the load cell on the sample mount track, the black arrow is the trajectory of the face of the mounted sample, and the dotted green line is the tensioned cable (highlighted).

Figure 4.5. Side view of sample mount area. White arrow shows the sample mount track projection, while the black arrow shows the path of the sample into the cable at tension. Cable location accented in green dashed line to indicate cable location.

The sample holder is comprised of a metal frame filled with ballistic grade silicone, welded to a bolt that screws directly to the load cell. The ballistic grade silicone was chosen for the cable abrader sample mount due to the durability of the material, as well as the similarity to the hardness of a tensed hand muscle. The sample holder currently being used has red silicone with a hardness of 60 Shore A, which is a medium hardness equivalent to the rubber for windshield wipers [43]. There are additional sample mounts that can be equipped on the machine if desired, one with 30 Shore A hardness and one with embedded thermistors. Due to the apparatus being very new, the decision was made to utilize the hardest silicone since it was potentially the most durable in case of unexpected material break through (a hole in the material), reducing the risk of damaging equipment. As the samples being tested did not produce noticeable frictional heat, the thermistor sample holder was not equipped.

The sample is designed to be held to the sample holder with clamps held to the left and right sides of the mount with bolts and wingnuts (Figure 3.4). The top and bottom of the sample are held to the mount using a set of small hook-and-loop straps that hook on the same bolts as the side clamps. With the clamps and straps equipped, the sample was held as close to flat as possible to the silicone surface of the sample mount (Figure 3.5).

Figure 4.6. Sample mount disconnected from load cell showing red silicone component used for indicator (left), and hook and loop straps used to secure the sample top and bottom to the sample mount area (right).

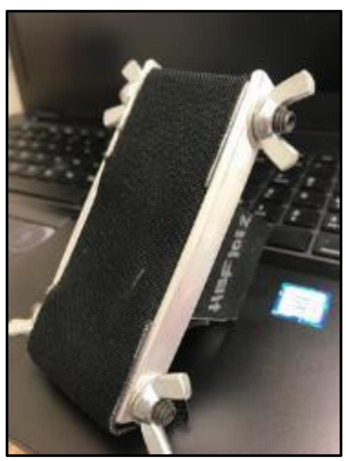


Figure 4.7. Sample of 2-layer laminated polyester cut in new shape placed on sample mount prior to equipping on cable abrader.

4.1.1.3 Software Monitoring

Sensors connected from the sample mount area to the load cell, which then send data to the on-board computer system and connected software. For use without the thermistors, the only aspect that was monitored was the sample pressure. The sample pressure is reflected in foot-pounds of torque due to the unique double coiled construction of the attached stainless-steel cable rope. Connection to the load cell and sample mount output the sample pressure via formulas in the software. The software used is a combination of two generic programs that work with the load cell set up, but the code used to properly display the information is proprietary to HDM. The load cell/sample mount’s y-direction is the rotational axis for the sample, the z-direction is for pressure perpendicular to the cable rope, and the x-axis is not used at this time. There are also connections for the thermistors in another sample mount to be used to show temperature if needed. There is a one-second sample rate for all data acquired that is shown on the on-board computer, and pressure shows in foot-pounds (ftlb) due to the cable exerting pressure on the sample in terms of torque due to the twisted construction of the wire cable rope. The observed scale can be adjusted as desired in terms of time scale across the software’s x-axis, and the y-axis in terms of the cable pressure. Figure 4.8 shows the cable pressure experienced by the mounted sample for one cable run for 250 feet.

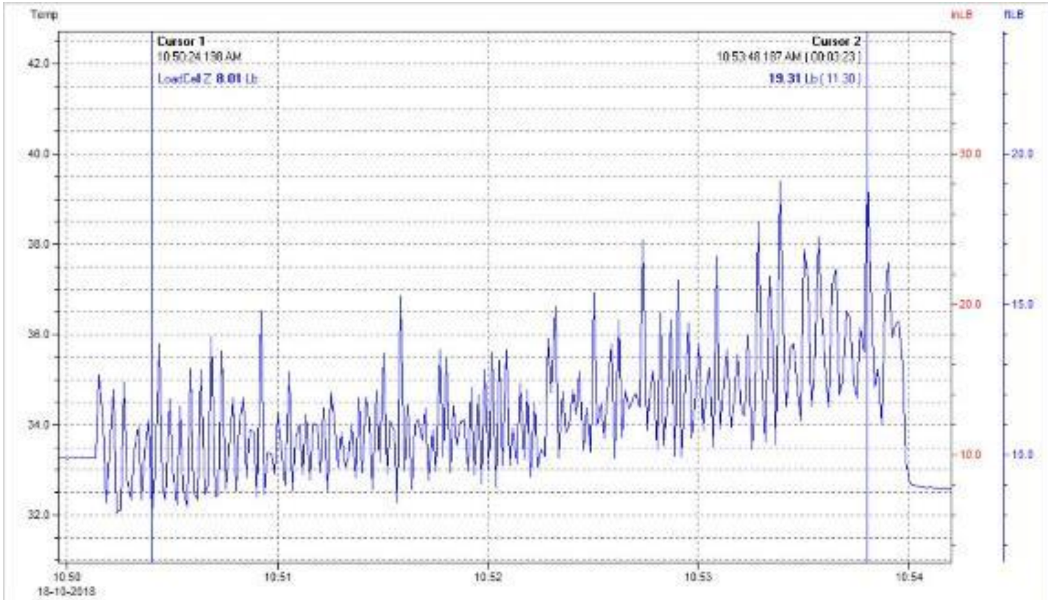


Figure 4.8. Screenshot of one cable run duration, monitoring sample pressure (ftlb).

4.2 Materials and Methods

4.2.1 Materials

The material used in the development of the linear concentrated abrasion testing method was a two layer laminated polyester material. The polyester was chosen due to it also being the base material that the SuperFabric™ dots are printed, and being readily available at the company for HDM where the cable abrader was developed. The polyester is naturally hydrophobic, which coupled with other fabric treatments to repel water, would not cause any potential issues with fouling the cable like moisture-swelled leather from destroyed hoist gloves. Figure 4.7 shows the base material loaded onto the cable abrader sample mount. HDM® were the principle investigators for the funded project, so the materials were pre-selected based on their requirements. SuperFabric® also is well-known for the material durability in commercial uses, such as sporting equipment, rugged upholstery, and protective clothing.

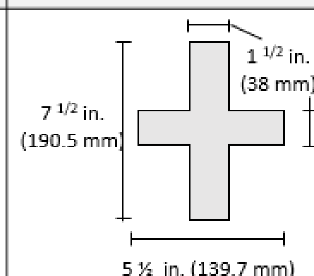
Table 4.1. Cable abrasion testing sample material information.

Type	Material Description	Average Thickness (mm)	Thickness Std. Dev. (mm)
HBF	two layered laminated polyester sheet	1.28	0.02

4.2.2 Methods

To process samples using the cable abrader in a consistent manner, a standard operating procedure (SOP) was established for the linear concentrated abrasion test method. Prior to beginning processing, five samples are cut in a cross-shaped pattern (7 ½" long x 5 ½"across x 1 ½" wide) and labeled, as seen in Table 4.2. Linear Concentrated Abrasion Tester (cable abrader) sample and testing information.

Table 4.2. Linear Concentrated Abrasion Tester (cable abrader) sample and testing information.

Apparatus	Material Tested	# of specimens	Sample Shape
Linear Concentrated Abrasion Tester (Cable Abrader)	Tough, highly abrasion resistant materials; industrial materials, leather, and helicopter rescue hoist glove materials.	**5 total**	

While the SOP addresses the basic components of cable abrasion, the operator still needs to be aware of changes in operating conditions including unusual noises during cable runs or cable problems (fraying/fouling). Issues encountered may not affect the sample processing specifically, but in the event it should be documented and published with the cable abrasion data. The sample is attached to the sample mount via the clamp and hook-and-loop system (Figure 4.6

and Figure 4.7), then screwed into the load cell securely. Tension is set on the cable via the brake system before the sample is moved to press into the cable at tension (10 ± 0.5 ftlb pressure). Next, the cable is ran in either the Cable Up or Cable Down direction at a speed of approximately 95 ft/min for 250 ft of cable rope passing over the sample. After the length is abraded, the machine is stopped and tension released from the cable. One complete "cable abrader cycle" is equal to two runs (one Cable Up and one Cable Down) or a total of 500 cable feet. The sample is checked for wear between Cable Up and Cable Down, with failure defined as a hole being visible in the material. The full cable abrader SOP can be located in Appendix A.

4.2.2.1 Determination of Sample Shape

Each sample is attached to the sample mount via clamps and the hook and loop system. To fit the sample mount and lie flush, the sample requires a specific shape so as not to interfere with the attaching bracket components. During the implementation of the sample mount straps, the sample shape needed to be reexamined. Previous forms of the sample shape allowed for the sides of the sample to be clamped down easily, but still needed further adjustment for the top and bottom portions of the sample to be properly secured. The sample was adjusted to cover the mount face only, with the top and sides extending out enough to be secured with the clamps and straps.

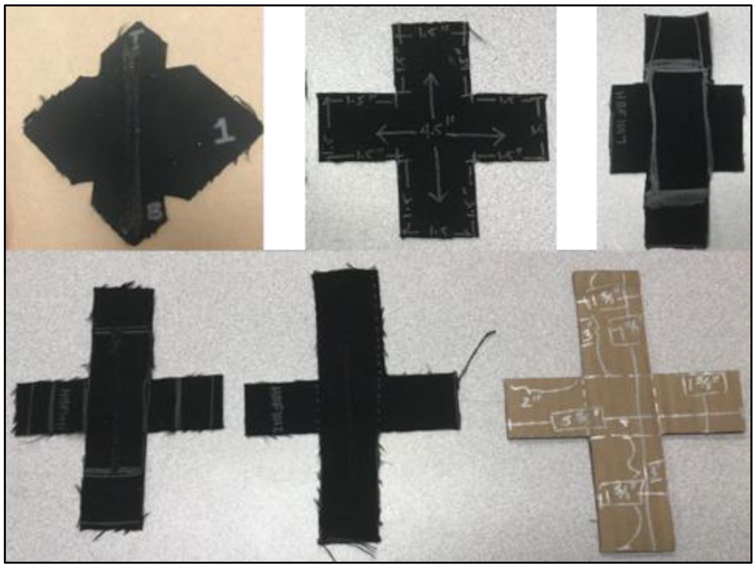


Figure 4.3. Progression of cable abrader sample shape: original (top left), simplified (top center), vertical length adjusted (top right), and optimized sample shape (bottom center).

After mounting and testing a few different sample designs, the testing sample template was determined to be a cross shape (Figure 4.1 and Figure 4.). The new sample shape removes bunching issues seen in previous versions and allows the sample to lay flat on the sample mount.

As with other abrasion testing methods, if any part of the sample is raised above the other portions, the raised portion will wear first and will not be representative of the actual conditions, which can produce skewed results. The new sample shape used in conjunction with the working sample mount system showed results representative of the actual abrasion performed, as well as consistency needed for testing.

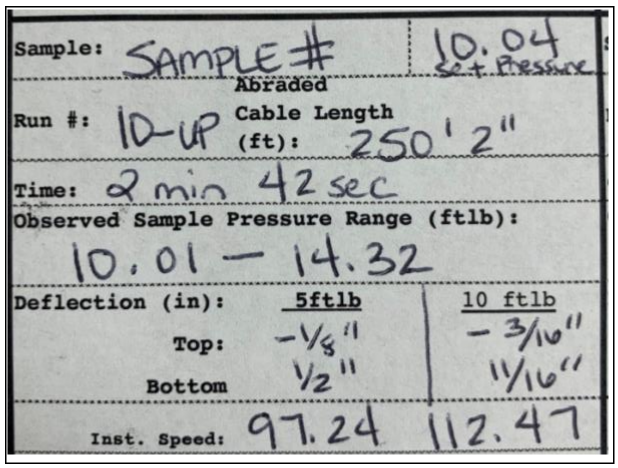
4.2.2.2 Determination of Testing End Point

The testing endpoint for the linear concentrated abrasion testing method was set to observing material failure, which is defined as a visual hole in the sample. Another option is to choose a specific endpoint based on the amount of cable abrader cycles, which can be set at any desired number, time and resources withstanding. The sample wear is checked visually between cable runs in either direction, and the process is stopped when the hole is visible. With the construction of the sample mount, the portion that the center of the sample abrasion area lies on is the red ballistic-grade silicone. When the samples have a failure, it is very visible due to the visibility of this bright red color. Smaller holes can indicate that the material failure occurred towards the end of that run, whereas larger holes can indicate that the material failed closer to the beginning of the actual run. Figure 4. shows the two-layer laminated polyester base material at a failure endpoint. The hole is at the top of the sample mount area and is easily seen due to the red silicone sample mount material reflecting the camera flash.

Figure 4.4. Polyester base material shown at material failure endpoint. Sample is shown on mount after four cable abrader cycles (left), with close up detail to show failure indicator visual of red silicone sample mount (right).

4.2.2.3 Explanation of Measured Parameters

The information measured throughout the cable run process can be broken down into two categories: abrasion resistance calculation variables and quality control variables. Abrasion resistance calculation variables are used directly in the quantification of a material's abrasion resistance, whereas the quality control variables are monitored to keep consistent results throughout the testing process. An example of the information recorded for one cable run can be seen in Figure 4.5. Cable abrader run data example entry for the 10th cable abrader cycle in Cable Up configuration. A template for the cable abrader run data sheet can be found in Appendix B.



Sample: SAMPLE # | 10.04 Set Pressure

Run #: 10-UP | Abraded Cable Length (ft): 250' 2"

Time: 2 min 42 sec

Observed Sample Pressure Range (ftlb):
10.01 – 14.32

Deflection (in):	5ftlb	10 ftlb
Top:	–1/8"	– 3/16"
Bottom	1/2"	11/16"
Inst. Speed:	97.24	112.47

Figure 4.5. Cable abrader run data example entry for the 10th cable abrader cycle in Cable Up configuration.

4.2.2.3.1 Abrasion Resistance Calculation Variables

The abrasion resistance calculation variables are used in the direct tabulation of information used to report data in terms of abrasion resistance, including the total abraded length, cable abrader cycle number, average speed, and machine run time.

The selected material for preliminary testing was a two-layer laminated polyester material, which was also the substrate material for the SuperFabric™. The samples were labeled with HBF (HDM Base Fabric) to indicate the origin of the material. Parameters measured included abraded length, cable abrader cycles, average cable speed, machine run time (t_{CA}), sample pressure variation (p_d), cable deflection (d_c), and mass difference. Results are gathered in terms of total abraded length (L_T), and machine run time (t_{CA}) by recording cable run time (cable up time t_{C^u}, cable down time t_{C^d}), abraded length per run ($cable\ up\ L_{rcu}\ or\ cable\ down\ L_{rcd}$), and number of cable abrader cycles (C_{CA}), all completed to either a specified end point or to failure. Average cable speed (S_{Cav}) was also calculated from the run time and the abraded length

In future iterations of the cable abrader apparatus, mass loss may also be possible to observe, but currently with the added mass gained from metal shaving deposits from the cable reels it is not plausible, since different materials tested showed to take on different levels of the weight. Similar to the Taber® abraser, having a soft bristle brush might be useful in eliminating debris not easily picked up via suction [4]. The following sections outline the correct way to calculate or measure the various parameters measured using the cable abrader.

4.2.2.3.1.1 Total Abraded Length Calculation

The total abraded length (L_T) was measured by using a rolling measuring tape on the moving cable near the sample mount area to record the number of cable feet that passed over the sample for each run direction. The run time was counted using a stopwatch and the calculated speed was recorded using the run time and abraded length to give the average cable speed for the whole run. Table 4.2 shows the formula used to calculate L_T, along with an example of how to apply the cable abrader data recorded with it. The total abraded length is necessary to tabulate due to the ability to equate amount of cable abrader feet to actual helicopter hoist cable feet, which can directly relate to the estimated lifespan of a material in those conditions.

Table 4.3. Calculation method for total abraded length for linear concentrated abrasion test method.

<table>
<tr><td colspan="2">Total abraded length, L_T is obtained by adding all cable lengths for all runs performed on one sample to the desired end point.</td></tr>
<tr><td>Equation:
$$L_T = \sum L_{rcu} + \sum L_{rcd}$$</td><td>Variables:
L_T = total abraded length in ft
L_{rcu} = abraded length for cable up run
L_{rcd} = abraded length for cable down run</td></tr>
<tr><td colspan="2">Example:

Cable Up, Run #1 = 250.25 ft, Cable Dn, Run #1 = 250.75 ft
Cable Up, Run #2 = 249.75 ft, Cable Dn, Run #2 = 250.25 ft
Cable Up, Run #3 = 250.00 ft, Cable Dn, Run #3 = 250.25 ft

$L_T = L_{rcu}$ (250.25 ft + 249.75 ft + 250.00 ft) + L_{rcd}(250.75 ft + 250.25 ft + 250.25 ft)

L_T = 1501.25 ft</td></tr>
</table>

4.2.2.3.1.2 Cable Abrader Cycles Calculation

The number of cable abrader cycles, C_{CA} was calculated by taking the values for each sample total abraded length and then dividing it by the length of one complete cable abrader cycle (500 ft). Table 4.4 the equation used to calculate C_{CA}, along with an example of how to apply the data as well. The cable abrader cycles are a relevant variable to monitor due to the easy direct comparison between the cable abrader cycle (500 ft) and a helicopter hoist complete cycle (approximately 500 ft depending on hoist model).

Table 4.4. Calculation method for cable abrader cycles for linear concentrated abrasion test method.

.**Cable abrader cycles,** C_{CA}, are obtained by adding the number of cable feet abraded, then dividing by 500 feet per cycle, or approximately the number of "Cable Up" and "Cable Down" runs completed.	
Equation: $C_{CA} = L_T \div (500\ ft\ /\ 1\ cable\ abrader\ cycle)$	Variables: C_{CA} = cable abrader cycles L_T = total abraded length in ft
Example: L_T = 1504 ft for all cable runs, recorded as "3 Cable Up runs and 3 Cable Down runs" in notes C_{CA} = 1504 ft ÷ (500 ft/1 cycle) C_{CA} = 3.008 cable abrader cycles, or approximately **3.01 cable abrader cycles**.	

4.2.2.3.1.3 Average Cable Speed Calculation

Table 4.5. The average cable speed, S_{Cav} was calculated using the cable length for one cable run and the recorded run time to give an approximation of the speed the sample experienced in that iteration.

<table>
<tr><td colspan="2">Average cable speed (S_{Cav}) is calculated by taking the total number of cable feet abraded for that run and dividing it by the amount of time the run to complete.</td></tr>
<tr><td>Equation:

$S_{Cav} = \ (L_{rcu}\ or\ L_{rcd}) \div (t_{C^u}$ or $\ t_{C^d})$</td><td>Variables:
S_{Cav} = average cable speed in ft
L_{rcu} = recorded feet for cable up run
L_{rcd} = recorded feet for cable up run
t_{C^u} = recorded run time for cable up
t_{C^d} = recorded run time for cable down</td></tr>
<tr><td colspan="2">Example:

Cable Up, Run #1: Total cable feet = 250.25 feet, time = 2 minutes 45 seconds

S_{Cav} = (250.25 ft) ÷ (2.75 min)

S_{Cav} = 91 ft/min</td></tr>
</table>

Table 4. shows the equation used to calculate S_{Cav}, along with an example of how to apply the data as well. The average cable speed is an important aspect to monitor due to the

Average cable speed (S_{Cav}) is calculated by taking the total number of cable feet abraded for that run and dividing it by the amount of time the run to complete.	
Equation: $S_{Cav} = (L_{rcu}\ or\ L_{rcd}) \div (t_{C^u}\ \text{or}\ t_{C^d})$	Variables: S_{Cav} = average cable speed in ft L_{rcu} = recorded feet for cable up run L_{rcd} = recorded feet for cable up run t_{C^u} = recorded run time for cable up t_{C^d} = recorded run time for cable down
Example: Cable Up, Run #1: Total cable feet = 250.25 feet, time = 2 minutes 45 seconds S_{Cav} = (250.25 ft) ÷ (2.75 min) S_{Cav} = **91 ft/min**	

relation with abrasion intensity, as well as being able to monitor the overall consistency of sample testing by keeping a consistent range of speed for all the samples.

Table 4.6. Calculation method for average cable speed for linear concentrated abrasion test method.

Average cable speed (S_{Cav}) is calculated by taking the total number of cable feet abraded for that run and dividing it by the amount of time the run to complete.	
Equation: $S_{Cav} = \ (L_{rcu}\ or\ L_{rcd}) \div (t_{C^u}$ or $t_{C^d})$	Variables: S_{Cav} = average cable speed in ft L_{rcu} = recorded feet for cable up run L_{rcd} = recorded feet for cable up run t_{C^u} = recorded run time for cable up t_{C^d} = recorded run time for cable down
Example: Cable Up, Run #1: Total cable feet = 250.25 feet, time = 2 minutes 45 seconds S_{Cav} = (250.25 ft) ÷ (2.75 min) S_{Cav} = **91 ft/min**	

4.2.2.3.1.4 Machine Run Time Calculation

The machine run time t_{CA}, (if to failure, $t_{CA}F$) can be calculated in three ways: by using the individual cable run times for all cable runs, adding the known individual running times for each run, or by using the general average speed of the cable running at run setting 6 (approximately 95 ft/min). The result obtained for either method will be relatively the same, but adding the individual run times could be tedious for items with higher cable abrader cycle numbers. In the case of a dropped formula in a spreadsheet, messy handwriting, or any other number of issues that could come with transferring data, the average cable speed is still possible to calculate. Table 4.7 shows the three methods used to calculate machine run time with the cable abrader.

Table 4.7. Calculation methods for machine run time for linear concentrated abrasion test method.

<table>
<tr><td colspan="2">Machine run time (t_{CA}) or machine time to failure ($t_{CA}F$) is calculated by average speed for a cable run in general (~95 ft/min) or it can be calculated by adding each individual cable run's measured time. To calculate the machine run time, take the total cable length abraded and divide by the average speed, either 95 ft/min or the special speed calculated for the run.</td></tr>
<tr><td>Equations:

#1 <u>Using base average cable abrader speed (95 ft/min)</u>
$$t_{CA} = L_T \div (95\frac{ft}{\min})$$
#2 <u>Using known individual run times</u>

$t_{CA} = \sum(t_{C^u} + t_{C^d})$

#3 <u>Using abraded length and cable speed if individual run time is not known</u>

$t_{CA} = for\ all\ runs\ [(L_{rcu}\ or\ L_{rcd}) \div (S_C)]$</td><td>Variables:
t_{CA} = machine run time in minutes
L_T = total abraded length in feet
L_{rcu} = recorded feet for cable up run
L_{rcd} = recorded feet for cable up run
t_{C^u} = recorded run time for cable up
t_{C^d} = recorded run time for cable down
S_C = cable speed for individual cable run</td></tr>
<tr><td colspan="2">Examples by approach:

#1: L_T = 1502.75 ft
t_{CA} = 1502.75 ft ÷ 95 ft/min
t_{CA} = 15.82 mins ≅ 15.8 min

#2:
Run #1: L_{rcu} = 250.25 ft; S_C = 98.91 ft/min; L_{rcd} = 249.75 ft; S_C = 93.54 ft/min
Run #2: L_{rcu} = 250.50 ft; S_C = 95.25 ft/min; L_{rcd} = 251.00 ft; S_C = 94.76 ft/min
Run #3: L_{rcu} = 250.92 ft; S_C = 95.44 ft/min; L_{rcd} = 250.00 ft; S_C = 96.90 ft/min

t_{CA} = t_{C^u}(2.53 min + 2.67 min + 2.63 min) + t_{C^d}(2.70 min + 2.65 min + 2.58 min)
t_{CA} = 15.76 min ≅ 15.8 min

#3:
Run #1: t_{C^u} = 2.53 min; t_{C^d} = 2.67 min
Run #2: t_{C^u} = 2.63 min; t_{C^d} = 2.70 min
Run #3: t_{C^u} = 2.65 min; t_{C^d} = 2.58 min

t_{CA} = 2.53 min + 2.67 min + 2.63 min + 2.70 min + 2.65 min + 2.58 min
t_{CA} = 15.76 min ≅ 15.8 min</td></tr>
</table>

4.2.2.3.2 Quality Control Variables

The quality control variables are used to maintain consistent operating conditions so repeatable results are possible, including cable deflection (d_c), sample set pressure, and sample pressure difference. Other parameters are also checked related to consistency of sample processing including the cable deflection in inches (d_C), set sample pressure in ftlb (p_0), and sample pressure difference ftlb (p_d).

4.2.2.3.2.1 Cable Deflection Measurement

Cable deflection (d_c), is measured to ensure that the amount of deflection to achieve 10.0 ± 0.50 ftlb sample pressure is consistent across all samples tested. Measuring cable deflection was done by using a ruler to observe distance between the starting position and the sample at correct pressure. The starting position for cable deflection is where the outside edge of the cable rope is 1 inch from the sample mount base plate, as seen in Figure 4.9. As the sample is pressed into the cable, the distance away from the original start point is the deflection. Sometimes the reel holding the cable will give slightly, causing a slight amount of slack in the cable, not immediately noticeable to the cable abrader operator; however, this phenomenon will be noticeable via the cable deflection and can be corrected if the cable is too loose. Cable deflection should be no less than ½ inch and no greater than 1 1/8 inches due to the increased amount of pressure it enforces on the sample, as well as the erratic cable run and jerking.

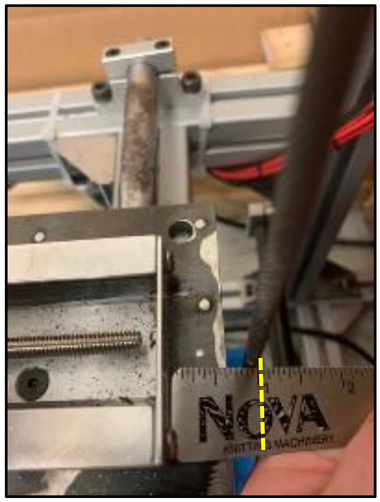


Figure 4.9. Top view of measuring cable deflection using a ruler for the cable abrader, shown at the neutral state with no sample pressure applied, and the cable at-tension position at one inch from the sample mount base frame (indicated by yellow dashed line).

4.2.2.3.2.2 Sample Set Pressure

Sample set pressure (p_0) is the actual pressure in ftlb that the cable abrader is set to prior to a cable run, which is obtained from the software connected to the load cell. While the general parameter has been set for the sample pressure being set initially at approximately 10.0 ftlb, there is still a ± 0.5 ftlb window that can potentially show variation in samples if not monitored. In recording the initial pressure the cable abrader was set to prior to a run, the stability of the cable and brake system can also be monitored over time. When the brake pads collect too much dust between the pads, the reels will roll forward instead of holding steady by the brake tension, which will also cause the amount of cable deflection required to increase to achieve the 10.0 ± 0.5 ftlb starting pressure.

4.2.2.3.2.3 Sample Pressure Difference

Sample pressure difference (p_d) is the difference between the two most extreme recorded pressures experienced by the sample during a cable run. During cable abrader runs the construction of the apparatus and slight elasticity of the cable itself can contribute to variations in pressure exerted on the sample. While some variation is unavoidable, the extent that this variation is occurring is important to monitor to keep conditions consistent between samples tested, as well as the constancy of the apparatus in the cable abrader operator's periphery.

4.3 Hypotheses

For this chapter, the hypotheses for the testing data are related to the reliability and repeatability of this developed test method using the cable abrader, specifically examining the testing parameters and the behavior of the two-layer polyester during testing.

First, for measured parameters all samples should appear to be consistent in abrasion resistance and operating conditions. Second, with the cable abrader runs, there could be a difference in the running conditions between cable up and cable down due to the construction of the machine or placement of the brakes, which could cause inconsistencies in sample abrasion. Third, the abrasion wear pattern for the cable abrader should be linear, with the failure point somewhere in the center of the sample face. Lastly, due to the characteristics of the base material, the failure point (visible hole) should appear after only a few full cycles of the cable abrader apparatus.

4.4 Results and Discussion

4.4.1 Results

The results were gathered using the individual run sheets, and then tabulated in to the following tables. Overall, the values for the average run time (Table 4.5. Cable abrader testing results for two layer laminated polyester samples machine run time in minutes, cable length abraded in feet, and calculated speed in ft/min were consistent across all five samples processed. The average speed varied slightly between Cable Up and Cable down, but did not appear to cause a significant difference in processing for the samples.

Table 4.5. Cable abrader testing results for two layer laminated polyester samples machine run time in minutes, cable length abraded in feet, and calculated speed in ft/min

		Run Time (min)			Cable Length Abraded (ft)			Calculated Speed (ft/min)		
		Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
HBF1013	Up	2.93	0.15	0.15	254.31	2.83	2.77	86.86	4.23	4.15
	Down	2.82	0.27	0.26	261.11	5.19	5.09	93.30	8.87	8.69
HBF1014	Up	2.81	0.08	0.07	259.93	6.55	5.74	92.68	3.77	3.30
	Down	2.72	0.22	0.19	251.27	0.61	0.53	92.71	7.03	6.16
HBF1015	Up	2.64	0.13	0.11	255.38	9.01	7.90	96.97	3.82	3.35
	Down	2.64	0.05	0.04	251.50	1.14	1.00	96.38	1.62	1.42
HBF1016	Up	2.54	0.04	0.04	250.52	0.28	0.27	98.60	1.67	1.64
	Down	2.61	0.07	0.07	250.92	1.19	1.17	96.25	2.39	2.34
HBF1017	Up	2.62	0.03	0.03	252.10	2.94	2.58	96.22	0.78	0.68
	Down	2.52	0.04	0.04	251.78	2.19	1.92	99.93	1.82	1.60

Similarly, the values for the set pressure difference was overall near the same value, hovering between 8 and 12 ftlbs. The set pressure and cable deflection were both closely monitored and adjusted within the desired ranges, so the narrow variation between those parameters is not surprising. Table 4.6. Cable abrader testing results for two layer laminated polyester samples set sample pressure in ftlb, pressure variation experienced by the sample, and cable deflection in inches at 10 ftlb sample pressure. shows the specific values for each of the quality control parameters.

Table 4.6. Cable abrader testing results for two layer laminated polyester samples set sample pressure in ftlb, pressure variation experienced by the sample, and cable deflection in inches at 10 ftlb sample pressure.

		Set Pressure (ftlb)			Sample Pressure Diff. (ftlb)			Cable Deflection @ 10ftlb (in)		
		Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
HBF1013	Up	9.72	0.37	0.36	10.96	3.00	2.94	0.88	0.09	0.09
	Down	10.14	0.34	0.33	9.52	1.22	1.20	0.66	0.06	0.06
HBF1014	Up	10.14	0.15	0.13	11.84	2.67	2.34	0.94	0.19	0.17
	Down	10.02	0.42	0.37	9.35	1.28	1.12	0.64	0.03	0.03
HBF1015	Up	10.21	0.21	0.18	13.63	1.43	1.25	0.96	0.10	0.09
	Down	10.15	0.26	0.23	8.92	1.59	1.39	0.68	0.05	0.04
HBF1016	Up	10.12	0.10	0.10	13.39	0.94	0.92	1.00	0.07	0.07
	Down	10.17	0.23	0.23	10.44	1.07	1.05	0.73	0.03	0.03
HBF1017	Up	10.25	0.28	0.25	11.71	2.10	1.84	0.96	0.15	0.13
	Down	10.32	0.06	0.05	8.74	1.15	1.01	0.86	0.16	0.14

Table 4.7 shows the values obtained before and after abrasion for sample mass. Due to the cable abrader depositing small pieces of metal in the surface of the sample as the cable passes over, the samples observed all gained at least 0.01 g mass instead of losing it, despite the visible hole left in the material. For this reason, it is not advised to report in terms of mass loss for the current iteration of the cable abrader.

Table 4.7. Mass loss in grams for two-layer laminated polyester samples on the cable abrader.

	Pre-Abrasion Mass (g)	Post Abrasion Mass (g)	Mass Loss (g)
HBF1013	6.25	6.26	-0.01
HBF1014	6.17	6.18	-0.01
HBF1015	6.18	6.19	-0.01
HBF1016	6.14	6.16	-0.02
HBF1017	6.09	6.10	-0.01

4.4.2 Discussion

For rescue helicopter hoist operations, the abrasive action produced by the hoist cable results in a particular style of wear that is not easily replicated in a laboratory setting. The linear concentrated abrasion test method using the cable abrader is a novel approach to testing the durability of materials with a focus on application and end-use. While the cable abrader was designed to mimic that specific abrasive action for the hoist cable during rescue operations, without consistency in sample treatment the discerning between material characteristics would not be readily apparent. After examining the preliminary data for the cable abrader for the various sample types, several themes emerge, with the first being that the cable abrader is a viable test method to appraise the abrasion resistance of materials in a simulated scenario for hoist operations. The red silicone sample mount backing works to quickly and easily identify material failure on the cable abrader apparatus and would be helpful in future iterations of the apparatus.

After examining the results for the cable deflection and run speed for each of the runs, the importance of maintaining stable sample run conditions was emphasized. Consistency of cable runs can be maximized by keeping the sample set pressure and cable deflection as close to the same values as possible. Inconsistent ability to attain similar sample pressure or cable deflection can be indicative of needing to perform maintenance on the brake system.

Using five samples per test is an adequate number to see any effect that might come from the material. Variation and inconsistencies for the abraded length and machine run time are due to the newness of the apparatus and human error, which could be fixed by automation or improved stopping mechanism.

The abrasion pattern for the cable abrader is linear vertically across the center of the sample, with pressure points at the top and bottom of the sample mount area, and the point of material failure is always at the top position. Not only did this action show to be consistent across all samples tested on the cable abrader, the sample pattern also mirrored the abrasion pattern observed for hoist gloves that were worn by actual hoist operators.

Finally, overall the linear concentrated abrasion test method is consistent, therefore any variations during testing of samples will be due to the properties of that material and not from variability in the cable abrader.

4.4.2.1 Linear Concentrated Abrasion Pattern by the Cable Abrader

As discussed in Chapter 2, one of the biggest differences between abrasion tests and results obtained from the tests is the mechanism of abrasion and the resulting wear pattern. In order to completely understand the capabilities of an abrasion test, the abrasion pattern must be identified and considered for application. After processing the five samples of the two-layer laminated polyester base material, the samples were examined for the wear pattern and amount of abrasion across the entire sample. The abrasion pattern can be seen in Figure 4.10, as a linear abrasion down the center of the sample face.

Figure 4.10. 2 layer laminated polyester sample after four cable abrader cycles.

The cable abrader mimics the specific abrasive action incurred from a hoist glove being pressed against an actively moving helicopter hoist cable back and forth. The abrasive action takes place at the vertical center of the mounted sample and the taut cable rope. The stainless-steel cable wire rope causes planar abrasions across the face of the sample, with the twisted construction of the wires also pulling some of the surface away from the sample. Sample pressure increases this frictional abrasion in the direction of the cable run, causing a linear concentrated abrasion pattern in the center of the sample mount in a vertical line down the entire length of the sample mount face. The sample has a slightly higher pressure at the top and bottom of the sample mount due to the position of the mount in relation to the cable, and thus wear may occur faster at those points.

Figure 4.11 shows a heat map of the general location of cable abrasion incurred by the base material samples. To have a comprehensive average of the abrasion area across all five of the base material samples, all five of the samples' abrasion locations were documented in one heat map drawing. The initial drawing was made in grayscale, and then colored afterwards to emphasize the amount of wear observed visually. The highest amount of observed abrasion was shown using red, especially in areas of a material failure (visible hole), and the lowest amount of observed abrasion was shown using violet to mimic the color spectrum and ease visual comprehension. The portion of the sample on the face of the sample mount was shown as gray, and the portions not possible for cable exposure or that were used in anchoring the sample to the mount were shown using the color white. The abrasion seen on from the cable abrader appears linear, vertical, and while there are abrasions across the linear length of the sample mount, there are areas of abrasion at the top and bottom of the sample mount. The top of the sample mount shows to consistently be the location where the material fails for all tested samples.

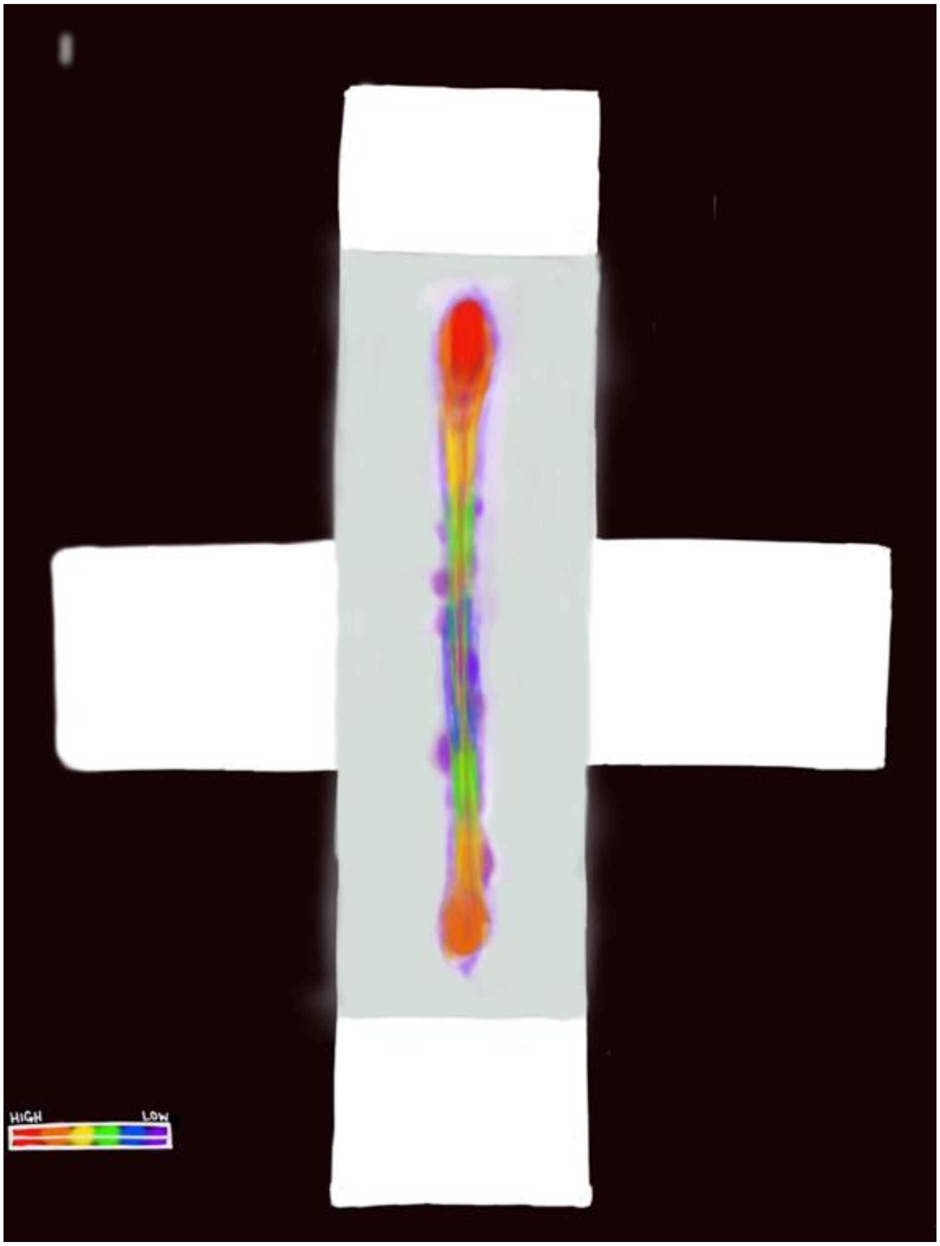


Figure 4.11. Abrasion heat map for two layer laminated polyester samples tested using the cable abrader apparatus. Red shows the highest amount of abrasion observed, and violet shows the lowest amount of abrasion observed.

4.4.2.2 Cable Abrader Maintenance

The stainless-steel cable rope should be replaced if fouling of the cable is noticed, specifically if the threads appear to be coming apart. Between 1500-2000 cycles, the cable should be verified to be in working condition or changed out to maintain proper abrasive action.

The brakes should be cleaned/wiped every 15-20 cycles; for longer testing lasting up to 30 cycles, clean afterwards; for shorter testing lasting 10 cycles or less, clean every two or three tests. Brakes can be cleaned by placing the manual gear in the neutral position and switching the brake power off. After the brake system has been powered off, the brake pads should be separated before threading a thin, lint-free cloth between the brake pads to remove any accumulated brake dust or debris in order to maintain proper working brakes for sufficient cable tension. After processing several sets of samples, brake dust might be noticed on the ground under the brake pads.

The lifespan of the cable wire rope used as the abradant is dependent on a few factors including visual inspection of the cable, types of materials abraded, and total number of cycles abraded. Regardless of how careful one is with setting the tension on the cable or stopping the cable abrader, the cable will eventually have a failure due to the constructed tension, with the inner wire rope wound one direction, and the other wound the other direction. Inspecting the cable between runs and/or slowly running the cable while wiping it down with a lint-free cloth are good ways to ensure the structural integrity of the cable is still sound enough to continue using. Similar to the “birdcaging” effect seen in Figure 2.11, any kind of visual changes where the cable wires appear to be separating need to be addressed by replacing the cable. Damaged cable still can cause uneven abrasions or break/unwind, causing damage to the cable abrader itself. The types of materials tested on the cable abrader will also make a difference in the failure point for the cable because of the construction of the cable. Similar to the metal shavings seen during this testing period, tiny pieces of the sample are carried away from the sample mount area via the cable wires. These pieces collect on the floor in front of the reels, but they occasionally would embed inside the cable, as was outlined by the BAA for this research. The leather used in current gloves would result in tiny pieces of the leather material working into the inner part of the cable, then swelling and causing structural damage to the cable when moisture or increased humidity was encountered. The cable abrader testing method has only been employed under dry conditions. The cable abrader does have the capability and attachment for wet samples, so preselecting materials based on their hydrophilic/hydrophobic properties should be considered in future iterations of test planning and improved machine design. Keeping track of the amount of cable abrader cycles tested is also important for wire rope's life cycle. For rescue helicopter hoist systems, cable failure means an unexpected reduction in resources in emergency response to a scene, as well as the potential for injury or death. To reduce the chance of a cable failure, the hoist cable in rescue helicopters are checked after every mission, as well as replaced after a certain number of cycles regardless of the actual working state of the cable. For most rescue helicopter models, the most common number is approximately 1500 complete cycles before the hoist manufacturer will come and swap the cable out for a brand new one [2]. While 1500 cycles might not be feasible to have a cable change with the cable abrader, it is still important to keep track of the number of cycles completed over the lifetime of the cable. A new wire rope for the cable abrader should at the very least be considered starting at the 1500 cycle point due to the cable's construction causing interior micro abrasions between the cable wires themselves as the cable ages.

Another component of the cable abrader system that will need maintenance is the silicone filling for the sample holder. The hardness of the silicone is robust at 60 Shore A, therefore it could take some time to work the material enough to have the cable pressure to noticeably wear the elasticity down. Depending on when the sample tested fails, there could be some direct contact between the cable and the silicone backing. This is not immediately destructive, but it should be monitored and replaced if the surface is noticeably damaged or cracks. At present, the best course of action for sample silicone maintenance will be to monitor the sample mount between tested samples for any degradation and to consider switching out the sample mount silicone around the same time the cable wire rope is changed.

4.4.2.3. Machine, Sample, and Operator Considerations

The cable abrader is the closest method to the abrasive action encountered during helicopter rescue hoist operations without actually being on-board the aircraft as it mimics the wear. There are still some limitations encountered including testing conditions, sample thickness, stability of cable wrapping around the reels, and the importance proper sample setting prior to cable runs.

A majority of the ASTM standard testing methods utilize standard laboratory conditions, which include conditioning in standard atmosphere for testing textiles (70 ± 2 º F or 21± 1 ºC, and 65 ± 2% relative humidity). For this project, the location of the apparatus was not in an area with those conditions available, thus samples cannot match other standard testing methods in that aspect since the samples could not have been conditioned due to space allocation. In general, the temperature range was around the standard temperature of 70 º F, but due to the open area where the apparatus was located, the relative humidity was unable to be regulated.

Another concern for using the cable abrader is that the reel system does not have an automatic feeder for the cable so the cable wrapping can cause the sample pressure to vary erratically during the cable runs. The cable wire rope tends to favor one side over the other depending on the reel until the tension pulls some of the wrapped loops over to the side, then causing a large drop in tension, which then translates to a drop-in sample pressure. At cable run setting 6, the speed appeared to have been slow enough to mitigate as much tension change as possible, but in future iterations of the test and cable abrader apparatus if a higher speed is desired, then a cable reel system with an automatic feeder should be strongly considered and is recommended.

For the cable abrader operator, an understanding of the cable abrasion process is necessary to obtain consistent results. One of the simplest parts of the cable abrasion test procedure that is the easiest to miss would be moving the sample mount to the correct position for the cable run direction. The construction of the cable includes wires wrapped around one direction in the core, and the opposite direction around the outside of the cable rope. This unique construction lends for extreme durability, but also will roll to one direction or the other depending on the surrounding space [45]. Moving the sample mount into the designated spot for the cable run direction corrects for the cable rolling motion and allows the cable to sit into a uniform groove in the center of the sample mount.

All of these individual concerns add more to the challenge of consistent results, but with careful monitoring and consistent running conditions can be mitigated to a reasonable degree.

4.4.2.4. Consistency of Linear Concentrated Abrasion Test Results

To show that the using the linear concentrated abrasion testing method is consistent, it must be shown that the variables examined during runs are also consistent.

In general, the greater amount of pressure that is exerted on a material the faster that the material is expected to have some sort of failure, whether that means a few broken yarns or a visible hole in the material. While the helicopter hoist cable has a wildly variable amount of pressure that can be experienced during rescue operations, the variation produced would not be repeatable in terms of a laboratory test. Due to the construction of the cable abrader, there is some natural variability that occurs in the pressure experienced by the sample, albeit limited.

Figure 4.12 shows the distribution of means for the base material sample pressure in ftlb difference between the minimum and maximum values experienced by the samples. Overall the distribution appears normal in shape for the 47 cable runs documented for these five samples. The normal quantile plot also shows the observed values in the normal range, which leads to the belief that it is reasonable to assume the conditions experienced by the base material was consistent. With the sample pressure difference showing consistently, it is clear that any differences in terms of measured abrasion resistance for the cable abrader will be due to the differences in fiber or yarn types in the materials tested.

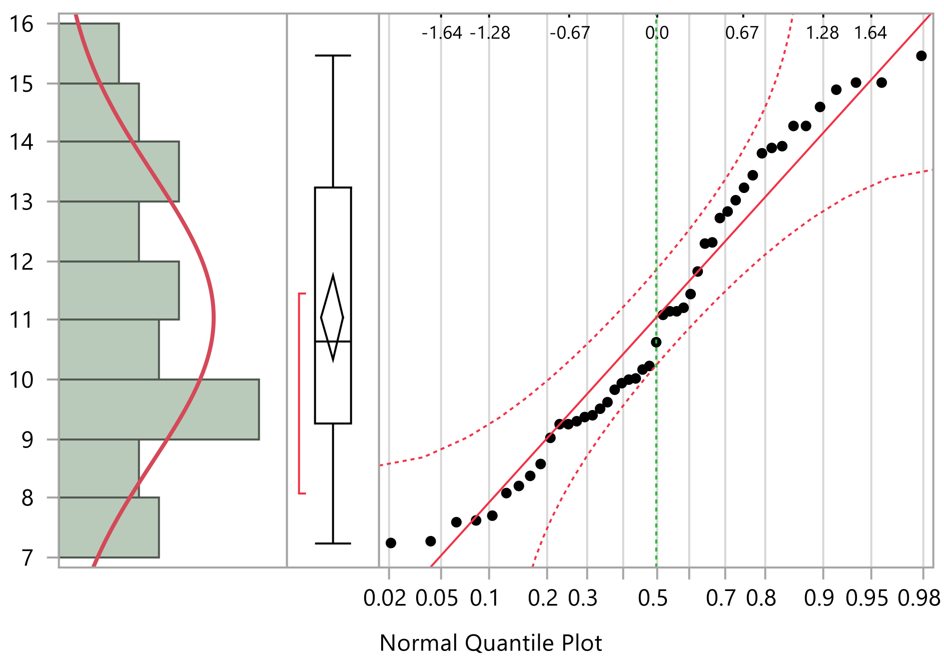


Figure 4.12. Mean distribution of cable abrader difference between maximum and minimum amount of pressure experienced by samples in ftlb.

Aside from the pressure variation on the sample, the speed at which the abradant is applied also must be consistent to have reliable test results. Figure 4.13 shows a similar finding to the pressure variation in that the distribution of the means of the measured speed in feet per minute. While the distribution does show some skew to the right, the normal quantile plot shows all values within the normal range so it is reasonable to believe that the values are consistent. With the speed appearing consistent across all the samples tested, it is also reasonable to believe that any differences in testing will be due to variations in the samples themselves.

Examining the abraded length for the polyester base material is needed to understand why there is some variation present in the data average table. For each cable run, 250 feet of the cable wire rope are supposed to pass over the sample. Due to operator error or any number of other reasons that would result in the cable abrader operator to being unable to stop it exactly at 250 feet each time. Figure 4.13, shows the mean distribution for the abraded length for all 47 runs performed on the base material samples.

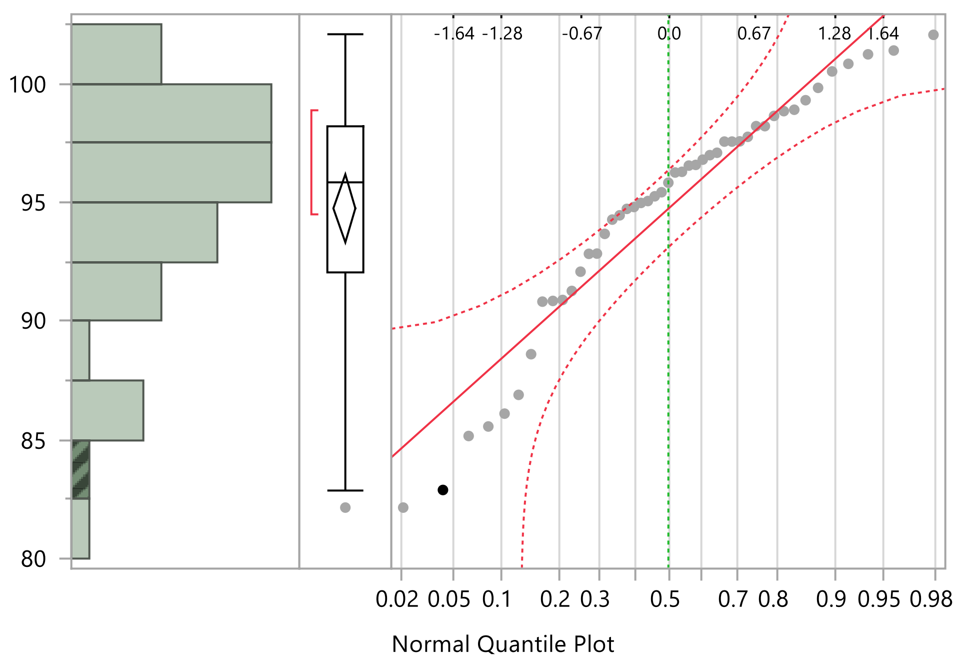


Figure 4.13. Mean distribution of cable abrader difference average calculated speed in feet per minute experienced by 2-layer laminated polyester samples.

For the helicopter hoist cable, one of the important components in mimicking that unique abrasive action is the intensity of the wear. The two variables that can be observed related to the intensity of abrasion are speed and force applied. In the case of the cable abrader, this means the force of cable pressure and speed will directly relate to the intensity of that abrasion. With the cable speed and pressure showing as consistent, a reliable side by side comparison of different materials can be performed.

For the quality control level measured variables, the cable deflection, Table 4.8 and 4.11 shows the data analyzed using JMP software.

Table 4.8. Quantiles for measured cable deflection examined using JMP statistical software.

100.0 %	maximum	1.125
99.5%		1.125
97.5%		1.125
90.0%		1.075
75.0%	quartile	0.9375
50.0%	median	0.75
25.0%	quartile	0.6875
10.0%		0.625
2.5%		0.625
0.5%		0.625
0.0%	minimum	0.625

Summary Statistics

Table 4.9. Summary statistics for cable deflection analyzed in JMP software.

Mean	0.8284574
Std Dev	0.1676383
Std Err Mean	0.0244526
Upper 95% Mean	0.8776779
Lower 95% Mean	0.779237
N	47

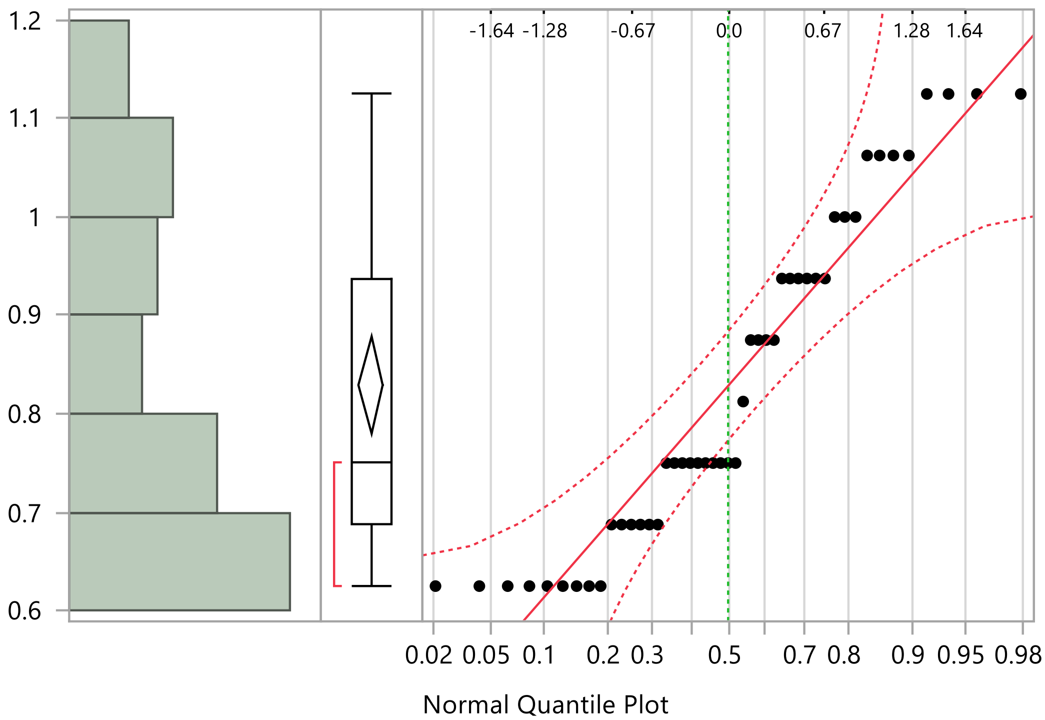


Figure 4.14. Mean distributions of cable deflection (in) at 10 ftlb sample pressure for cable abrader testing.(N=47)

4.5. Conclusions

The linear concentrated abrasion test method using the cable abrader is a novel approach to testing the durability of materials with a focus on specific application and end-use.

Consistency of cable runs can be maximized by keeping the sample set pressure and cable deflection as close to the same values as possible. Inconsistent ability to attain similar sample pressure or cable deflection can be indicative of needing to perform maintenance on the brake system. The monitored parameters during a cable abrasion test run are consistent across all five samples, and any variations found in the sample data are most likely from properties of the two-layer laminated polyester material. The speed of the cable abrader is slightly different depending on the cable direction, but not different enough to affect the results. Using five samples per test is an adequate number to see any effect that might come from the material, such as variation between samples of the same material. Variation and inconsistencies for the abraded length and machine run time are due to the newness of the apparatus and human error, which could be fixed by automation or improved stopping mechanism.

For measured parameters for the linear concentrated abrasion test method, the samples should are reasonably consistent in terms of abrasion resistance and operating conditions. With the cable abrader runs, there could be a difference in the running conditions between cable up and cable down due to the construction of the machine or placement of the brakes.

The abrasion pattern for the cable abrader is linear vertically across the center of the sample, with pressure points at the top and bottom of the sample mount area, and the point of material failure is always at the top position.

Overall the linear concentrated abrasion test method is consistent, therefore any variations during testing of samples will be due to the properties of that material and not from variability in the cable abrader. This test method is a good representation of rescue hoist cable abrasive conditions, and would be a good choice to test hoist glove prototype materials.

CHAPTER 5 . MATERIAL ASSESSMENT OF ABRASION RESISTANCE USING LINEAR CONCENTRATED ABRASION TEST METHOD WITH CABLE ABRADER

5.1. Introduction and Background

The cable abrader is a new machine that was fabricated by Higher Dimension Materials (HDM out of Minneapolis, MN) specifically for testing materials related to the hoist glove project. Due to the newness of the machine and relation to the helicopter hoist cable abrasion mechanism, the test method to use the apparatus had to be developed. After the initial data parameters for the machine were selected with regard to end-use application and testing of samples was performed, it was shown that the cable abrasion test method was consistent. The consistency for the testing method provides a reliable baseline where tested materials can be compared knowing that the differences in testing results are from material properties, not likely to be variations in the apparatus or test method. Using the developed testing method, three categories of samples were tested including leathers comparable to the thicknesses of hoist gloves preferred by the hoist operators, baseline gloves, and SuperFabric™ samples. Visual assessment of the sample also occurs in testing with the Wyzenbeek and Taber® abrasion machines, with one cycle also being one full motion of the abradant across the material's surface. The material was abraded using the cable until the material failed, which was defined as the material having a visible hole. With this information and sampling, reasonable comparisons could be made regarding the variability of those materials.

5.2. Materials and Methods

5.2.1. Materials

Material testing for this research is comprised of three categories: baseline leather, baseline gloves, and leather alternative materials. All categories of materials and their descriptions can be seen in Table 4.2. The baseline leather samples were chosen due to their similarity to two of the hoist glove types in terms of material thickness, and all four of the leather samples came from pelts.

5.2.1.1. Selection of Baseline Materials

Baseline materials were selected with consideration to materials currently being used for rescue hoist scenarios by responders. Baseline materials are broken down into two categories: baseline gloves and baseline leather materials.

Through market research and observations from the helicopter hoist training, four glove types were identified for initial testing. The gloves used are labeled BLE, BLF, BLG, and BLH (Table 5.1) The BLE type Hardy® brand is a thin yellow work glove with gel padding in the palm and the finger regions, and is the desired level of dexterity for most of the hoist operators that shared opinions regarding preferences. The BLE gloves are affordable at less than $10 per pair, but are usually destroyed by the hoist cable after one mission. BLE is only made in two sizes (Large and Extra Large) with limited availability due to the Large size being available only in outlet home improvement shops and the Extra Large size only being available online through the same retailer. To combat the glove variety issue, a similar leather glove type in terms of material thickness was chosen, BLF, from the LifeSaving Systems Corp®. Company. The BLF gloves are available in sizes Small up to Extra-Extra Large from their online shop. The BLG type is the most expensive and specialized hoist glove by Priority 1® company, made of microfiber, thicker formed palm leather, and para-aramid fiber stitching. These gloves reportedly last a few rescue missions, but still become worn pretty quickly and require a day-long break in period before the glove is comfortable to wear. The increased specialization and durability also comes at a higher price point, retailing online around $80 for one glove. Also, the BLG glove type also has very limited availability due to manufacturer restrictions on purchasing.

Glove style BLH is a summer flyer type flight glove that is generally worn by aircrew members due to regulation, and sometimes underneath the hoist glove if regulated to do so. The gloves represent the benchmarks set for the glove prototype in terms of acceptable flexibility and durability based on user feedback. BLE is the type of glove preferred by responders in San Francisco due to the flexibility and comfort but with durability as the main concern as they can observe wear in as little as one mission. BLG is another glove used by responders that has a much higher amount of durability but is less flexible. BLF is a glove similar to BLE in terms of durability and was chosen based on market availability. BLH is a summer flyer style flight glove that would be worn in configuration with the over glove.

For additional data comparison points, leather samples were acquired with similar characteristics to the gloves in terms of material thickness and durability. The baseline leather selections are indicated by the labels BLA, BLB, BLC, and BLD (Table 5.1). BLA's material is a thin pig skin leather, approximately the same thickness as the thin leather used in the glove types BLE and BLF. Material types BLB, BLC, and BLD are all different thicknesses of cow skin leather that has been treated to be oil and water resistant, and normally is used for manufacturing gaskets. The type BLC is a similar thickness to the leather in glove BLG and would ideally serve as an analogous comparison in terms of the durability.

Table 5.1. Reference chart of materials used for testing via linear concentrated abrasion method with cable abrader.

Type	Material Description	Average Thickness (mm)	Thickness Std. Dev. (mm)
BLA	pig skin leather sheet	0.96	0.05
BLB	cow skin leather sheet, oil and water resistant	4.21	0.12
BLC	cow skin leather sheet, oil and water resistant	2.68	0.48
BLD	cow skin leather sheet, oil and water resistant	5.27	0.07
BLE	Hardy ® glove, work style, padded leather	1.02	0.00
BLF	Lifesaving Systems Corp®. hoist operator glove, leather	1.54	0.13
BLG	Priority 1® hoist operator glove, leather and Nomex	3.06	0.06
BLH	summer flyer style flight glove, leather and Nomex	1.35	0.02
SFA	single layer SuperFabric™ sheet, 600 denier, stormcloud grey color	1.04	0.01
SFB	two-layer SuperFabric™ sheet, 600 denier, mushroom color	1.56	0.01
SFC	two-layer SuperFabric™ sheet, 600 denier, hex grey color	1.55	0.02
SFD	single layer SuperFabric™ sheet, grey	0.66	0.00

5.2.1.2. Selection of Leather Alternative Materials

Almost all of the hoist gloves used by operators are made with leather material, which generally has a good reputation for being durable as well as comfortable for the wearer. The issue in this case lies in the fact that small pieces of the leather glove can become embedded in the cable and foul the cable from the inside outwards. Leather is inherently affected by humidity and moisture, so when damp conditions occur, the leather inside the cable can swell, dislodging the hoist cable wires [2]. This destructive process of the cable by the leather serves as the foundation for this research, with direct emphasis on the need for non-destructive alternative materials.

HDM, the company that developed the cable abrader, mainly specializes in materials consisting of a base material covered in small heavy-duty printed ceramic dots that results in considerable resistance to wear. The durable construction of this material also allows for relatively thin materials to have comparatively extreme abrasion resistance to other materials with a similar thickness. These unique qualities combined with a hydrophobic substrate like polyester makes for a material application that could result in a durable hoist glove that also is lighter weight and non-destructive to the cable. This material type is called SuperFabric™, and is available in a number of different colors, substrates, weights, and patterns. Overall, most of the details of the SuperFabric™ types are proprietary, the four sample types were pre-selected by HDM due to being highly abrasion resistant in internal laboratory testing using a Taber® abraser. The SuperFabric™ sample types are SFA, SFB, SFC, and SFD. SFA is a single layer, 600 denier material with stormcloud grey dots. SFD is also a single layer material that showed to be very abrasion resistant during internal Taber® abrasion testing. SFB and SFC are both two-layer sheets, with SFB in mushroom, and SFC in hex grey. SFD is the thinnest in terms of material average thickness, followed by SFA showing almost 0.5 mm thicker. SFB and SFC are both around 1.5 mm thick. A reference chart for all the materials tested can be found in Table 5.1, and SuperFabric® samples can be seen in Figure 5.1.

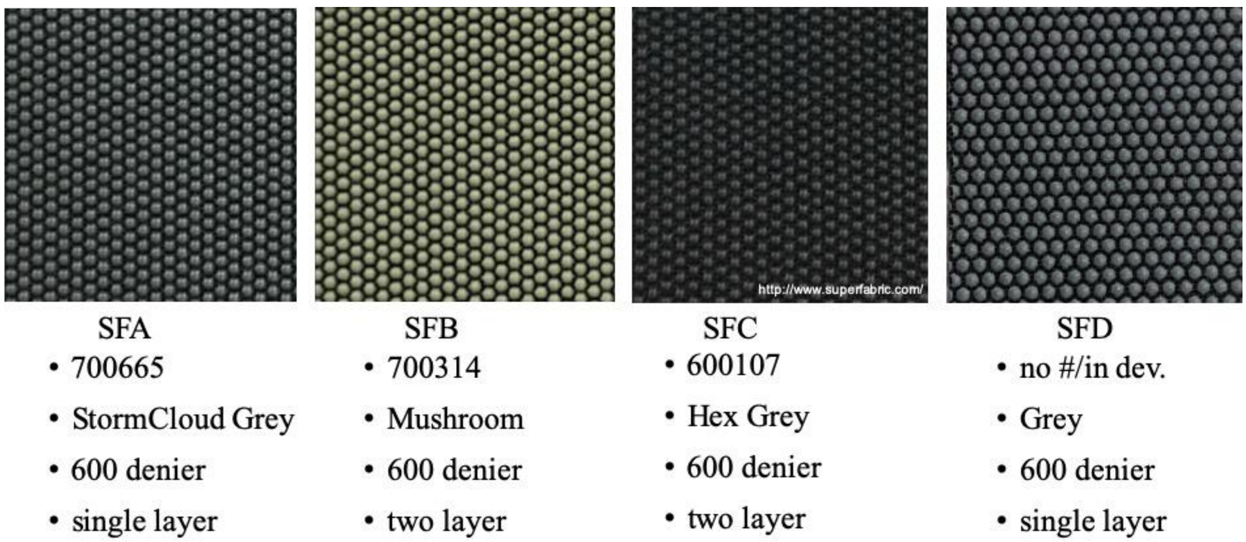


Figure 5.1. SuperFabric® sample comparison.

All samples were prepared and tested according to the newly developed linear concentrated abrasion test method using the cable abrader. Five samples of the baseline leather and SuperFabric™ material samples, and three samples each of the baseline glove materials were prepared with the cross sample shape (Figure 5.2) (Due to material availability restrictions, only three of the gloves were available for testing, and were cut out of the already produced commercially available glove with a focus to capture representative abrasion in a modified manner with the glove construction). The samples were attached to the sample mount via the clamp and hook-and-loop system then screwed into the load cell securely. Tension was set on the cable via the brake system before the sample is moved to press into the cable at tension (10 ±

0.5 ftlb pressure). Next, the cable was ran in either the Cable Up or Cable Down direction at a speed of approximately 95 ft/min for 250 ft of cable rope passing over the sample. After the length was abraded, the machine was stopped and tension released from the cable. One complete “cable abrader cycle” is equal to two runs (one Cable Up and one Cable Down) or a total of 500 cable feet. The sample is checked for wear between Cable Up and Cable Down, with failure defined as a hole being visible in the material. Results were then compiled and analyzed by calculating the averages, standard deviation, and 95% confidence interval across the material types for all samples; statistical analysis was also performed using JMP software.

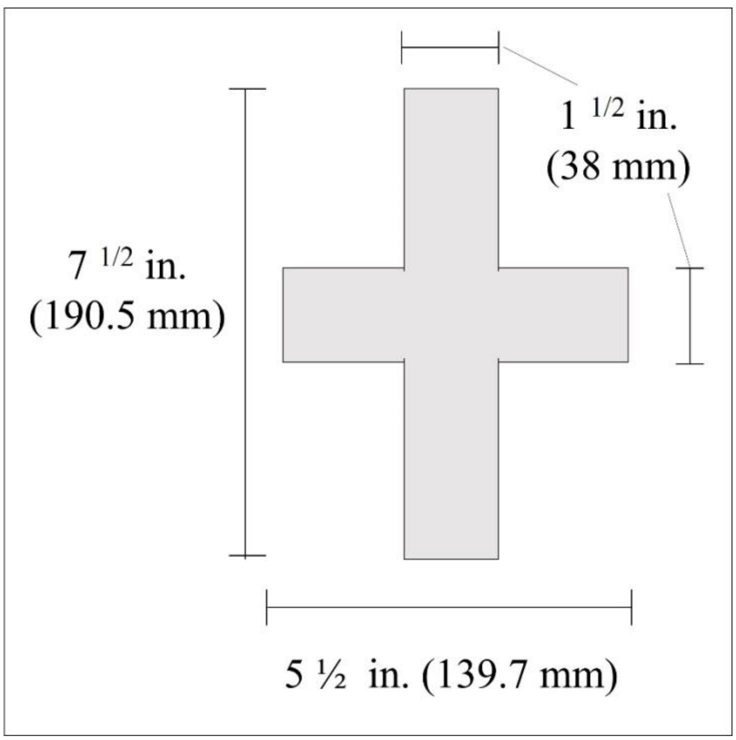


Figure 5.2. Sample template for linear concentrated abrasion test method using cable abrader apparatus.

5.3. Hypotheses

In examining these different abrasion tests, there are a few hypotheses that could occur. The SuperFabric™ could be more durable or equal to the baselines by thickness in terms of machine time to failure or stop. The SuperFabric™ could also be more durable or equal to the baselines by thickness in terms of abraded length to failure or stop. The SuperFabric™ is better than or equal to the baselines by thickness in terms of cable abrader cycles to failure or stop. Also, the leathers should show to be good representations of the glove types in terms of cable abrader cycles to failure

5.4. Results and Discussion

5.4.1. Results

Results were gathered using the developed linear concentrated abrasion test method and cable abrader apparatus. Cable run data was taken for cable run time in minutes, cable length abraded in feet, and calculated cable speed in feet per minute. Monitored set parameters were also documented by recording sample set pressure in ftlb, sample pressure difference in ftlb via computer software, and cable deflection in inches. All of the parameters were recorded for each of the sample types, averaging the data, as well as obtaining the standard deviation and 95% confidence interval.

5.4.1.1. Baseline Leather Abrasion Testing Results

Table 5.2. Baseline leather sample results for cable abrader testing,, with machine run time in minutes, abraded length in feet, and calculated cable speed in feet per minute.

	Run Time (min)			Cable Length Abraded (ft)			Calculated Speed (ft/min)		
	Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
BLA	8.36	2.14	1.88	802.05	209.80	183.90	95.99	1.38	1.21
BLB	157.05	3.50	3.07	15048.94	17.11	15.00	96.00	2.03	1.78
BLC	161.01	9.05	7.93	15385.78	715.08	626.78	95.73	1.13	0.99
BLD	158.97	1.81	1.59	15025.94	15.71	13.77	94.66	1.16	1.02

Table 5.3. Baseline leather sample results for cable abrader testing,, with sample set pressure in ftlb, sample pressure difference in ftlb during cable run, and cable deflection in inches at 10 ftlb sample pressure.

	Set Pressure (ftlb)			Sample Pressure Diff. (ftlb)			Cable Deflection @ 10ftlb (in)		
	Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
BLA	10.35	0.22	0.19	7.52	1.55	1.36	0.67	0.03	0.03
BLB	10.26	0.01	0.01	8.85	0.43	0.38	0.80	0.01	0.01
BLC	10.29	0.04	0.04	10.14	0.94	0.82	0.79	0.04	0.04
BLD	10.24	0.02	0.02	8.74	0.57	0.50	0.77	0.03	0.03

5.4.1.2. Baseline Glove Abrasion Testing Results

Table 5.4. Baseline glove sample results for cable abrader testing,, with machine run time in minutes, abraded length in feet, and calculated cable speed in feet per minute.

	Run Time (min)			Cable Length Abraded (ft)			Calculated Speed (ft/min)		
	Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
BLE	39.85	12.91	14.61	3842.34	1266.10	1432.70	96.36	0.92	1.04
BLF	61.36	4.48	5.07	6014.71	508.61	575.54	98.04	1.18	1.34
BLG	119.87	10.33	11.69	11696.69	1034.89	1171.07	97.62	0.27	0.30
BLH	18.06	2.87	3.25	1753.83	252.47	285.69	97.15	1.43	1.62

Table 5.5. Baseline glove sample results for cable abrader testing,, with sample set pressure in ftlb, sample pressure difference in ftlb during cable run, and cable deflection in inches at 10 ftlb sample pressure.

	Set Pressure (ftlb)			Sample Pressure Diff. (ftlb)			Cable Deflection @ 10ftlb (in)		
	Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
BLE	10.24	0.01	0.01	10.63	2.17	2.46	0.76	0.04	0.05
BLF	10.29	0.02	0.02	8.82	1.10	1.24	0.80	0.03	0.03
BLG	10.25	0.03	0.03	10.19	0.50	0.57	0.84	0.02	0.02
BLH	10.28	0.06	0.07	7.90	0.87	0.98	0.75	0.04	0.05

5.4.1.3. SuperFabric™ Abrasion Testing Results

Table 5.6. SuperFabric™ sample results for cable abrader testing,, with machine run time in minutes, abraded length in feet, and calculated cable speed in feet per minute.

	Run Time (min)			Cable Length Abraded (ft)			Calculated Speed (ft/min)		
	Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
SFA	87.59	35.74	31.32	8451.13	3519.17	3084.63	96.25	1.02	0.89
SFB	139.63	19.91	17.45	14102.83	127.58	111.83	96.06	0.65	0.57
SFC	204.22	23.21	20.34	18908.67	791.30	693.59	94.11	0.47	0.42
SFD	45.61	23.14	20.28	3784.65	1902.37	1667.47	92.72	2.40	2.11

Table 5.7. SuperFabric™ sample results for cable abrader testing,, with sample set pressure in ftlb, sample pressure difference in ftlb during cable run, and cable deflection in inches at 10 ftlb sample pressure.

	Set Pressure (ftlb)			Sample Pressure Diff. (ftlb)			Cable Deflection @ 10ftlb (in)		
	Average	Std. Dev.	95%CI	Average	Std. Dev.	95% CI	Average	Std. Dev.	95% CI
SFA	10.26	0.04	0.04	9.77	0.73	0.64	0.77	0.04	0.04
SFB	10.24	0.03	0.03	9.22	0.99	0.87	0.78	0.02	0.02
SFC	10.23	0.06	0.05	8.76	0.63	0.55	0.73	0.00	0.00
SFD	10.26	0.01	0.01	10.61	1.18	1.03	0.76	0.04	0.04

5.4.2. Discussion

The initial set pressure for the cable run is also a testing condition that requires consistency. Figure 5.3 shows the mean distribution of the set sample pressure in ftlb for all 2078 of the runs examined for the materials comparison. The distribution appears relatively normal overall, and the normal quantile plot shows almost all values in that normal range. The maximum value for the set pressure for these samples was 10.67, initially showing as an outlier in terms of the desired range at first glance, but can be rationalized by understanding the pressure for the load cell/sample mount does not necessarily have to start out at zero. For the thicker leather materials, the stiffness of the material can actually push back onto the load cell and skew the computer reading of the pressure. Depending on the positioning of the stiff material, it can show the sample pressure (without cable tension) as a positive value. In one particular case, it was noticed that the sample pressure was 0.18 ftlb prior to any actual cable pressure to be applied. Knowing that the desired range for the sample set pressure is 10 ± 0.5 ftlb, the maximum value to aim for in setting the pressure is 10.50 ftlb. However, with the stiffer leather material skewing the actual pressure, a 0.18 ftlb starting untensioned pressure added to the 10.5 ftlb max value is 10.68 ftlb. With this in mind, the 10.67 ftlb “outlier” value is actually still within a normal range. After examining the data for the sample set pressure for all of the material types, it is reasonable to say that all of the samples were tested consistently so the differences in terms of abrasion resistance would be due to differences in the materials.

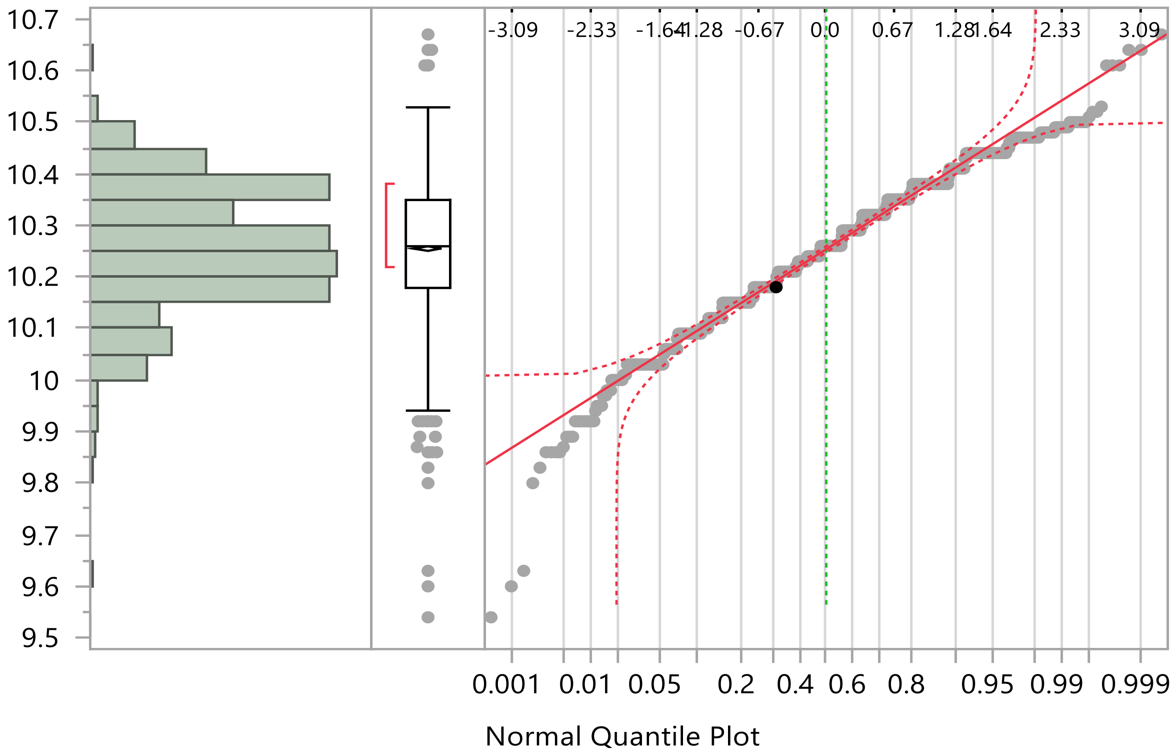


Figure 5.3. Mean distribution of set sample pressure in ftlb for all tested sample runs (N=2078).

Figure 5.4 shows a one-way analysis of the difference between the maximum and minimum amount of pressure experience by the sample via cable in ftlb during a cable run separated by material type. All of the boxes for the means are approximately in the same position, so it is reasonable to say that the means for all sample types are relatively equal in terms of pressure difference. The normal quantile plot lines also have similar slopes, which also points to the means reasonably being approximately the same. This similarity in means for the sample pressure difference for all the samples shows that it is reasonable to state that all of the samples tested experienced similar conditions during the cable runs, and that the testing method overall is relatively consistent.

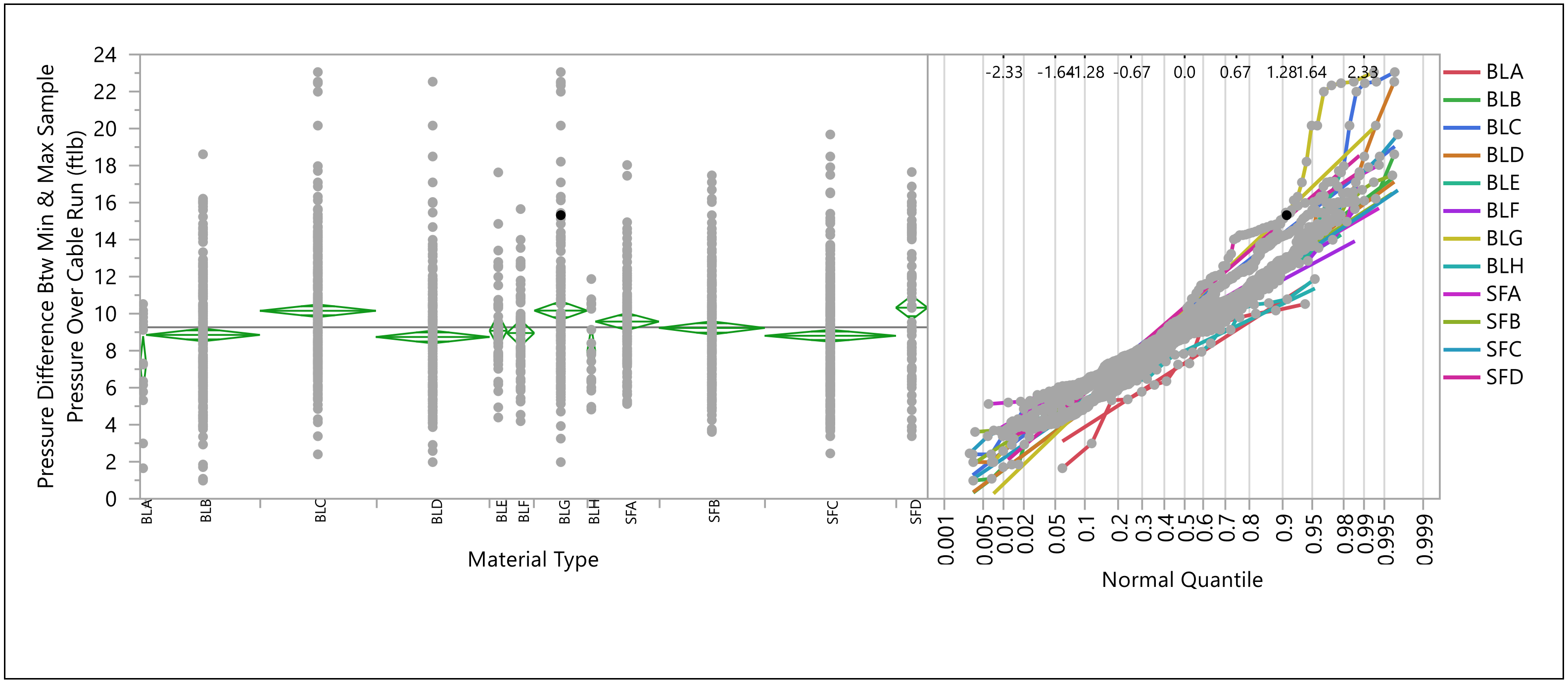


Figure 5.4. One-way analysis of difference between minimum and maximum sample pressure (ftlb) experienced over the course of cable run by material type.

5.5. Conclusions

With the cable abrader apparatus already shown to be a consistent testing apparatus used in the linear concentrated abrasion test method, materials tested using those parameters should illuminate differences in material characteristics. The SuperFabric® was more durable than the baseline materials by thickness in measured machine time. Likewise, the SuperFabric® samples were also more durable than the baselines in abraded cable length, meaning that they could withstand longer use in a similar scenario for helicopter hoist operations. The leather materials had similar failure rates to the gloves, showing that they are good representations of the gloves on a material level. Because the testing conditions were consistent, the differences in the measured abrasion values were due to material characteristics, not variations in the testing apparatus. If the cable abrader shows to be equal to or better in terms of time to failure/machine run time and abraded length, then the use of the cable abrader in other testing could be justified, and even pushed towards being a new ASTM standard.

CHAPTER 6 . VIABILITY OF ABRASION TEST METHODS FOR HELICOPTER HOIST CABLE REPRESENTATION

6.1. Introduction and Background

The abrasions caused by a rescue helicopter hoist cable are concentrated and linear across the palm and fingers of the hoist operator's protective glove. In order to choose test methods that can replicate that specific abrasion style, the mechanism of abrasion must closely mimic the hoist cable in terms of wear pattern, intensity, and concentration. In order to effectively compare the different abrasion test methods for replicating the hoist abrasion, the mechanism of each test method needs to be considered. The applicable test methods, in this case the Taber®, Wyzenbeek, and the cable abrader, all tested the same set of materials; Data from these methods were compared against each other for accurate hoist abrasion representation.

6.1.1. Wyzenbeek Abrasion Tester

The Oscillatory Cylinder Abrasion Tester, or Wyzenbeek machine, is comprised of an oscillating cylinder equipped with clamps for mounting, four specimen holding arms, two different calibrated masses, thumb screw, sponge rubber pressure pad, two slotted vacuum pipes, and an automatic cycle counter [6]. In order to attempt to simulate the stainless-steel rescue hoist cable, the abradant chosen will be the stainless steel mesh screen. The most common head pressure used is 13.4 Newton (N) or 3 pounds of force (lbf) with 17.8 N or 4 lbf specimen tension, which would work for general to heavy duty upholstery end uses, but would not be suited for extremely abrasion resistant materials due to the time and energy needed to make any worthwhile abrasions; the caveat to this is that there would be little if any abrasions visible at all due to the relative low pressure on the material and abrasive aggressiveness of the available abradants for more abrasion resistant materials.

The abrasion occurs at the contact point where the sample is held taut in place while the specific abradant sheet fixed to the oscillating cylinder rubs back and forth. Abrasion intensity can be adjusted using sample tension, head weight, or abradant screen choice. Visually, abrasion shows as a linear area across the width of the material in the center of the sample, which can be seen in Figure 6.1.

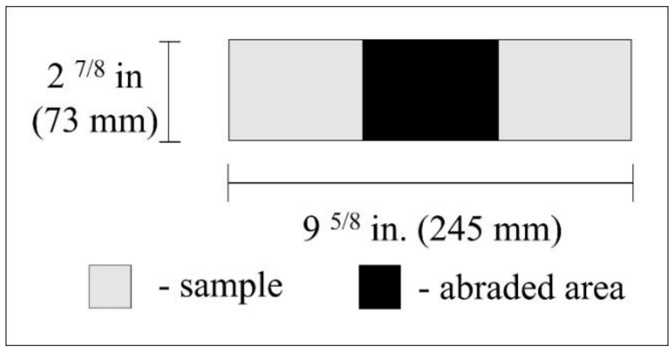


Figure 6.1. Abraded area for samples tested with Wyzenbeek abrasion tester.

6.1.2. Taber® Abraser

The rotary platform, or most commonly the Taber® abraser is comprised of a removable turntable platform with a rubber pad, clamp plate and knurled nut, and clamp ring to secure the specimen; pivoted arms that attach to the abrasive wheels and weights, platform rotating motor, vacuum nozzle and cleaner for debris removal, and revolution counter [8]. Abrasion setup involves using specialized abradant wheels, Calibrade® Taber® abrading wheels, with a specified weight up to 1000 grams. Calibrade® is composed of a non-resilient, vitrified binder and aluminum oxide or silicon carbide abrasive particles. Abradant wheels vary in abrasive texture, with applications ranging from abrading delicate textile fabrics to heavy duty automotive carpet materials. While the abradant wheels are more aggressive than the abradant fixed to the oscillating drum of the Wyzenbeek mentioned previously, the abrasive conditions for the Taber®

are circular, relatively flat. For this research, the abradant used will be the H-18 coarse Calibrade® wheels with a 1000 g weight applied.

For this testing method, the abrasion occurs at the contact points where the two abradant wheels roll across the face of the sample as the platform rotates. Visually, abrasions show in a circular pattern relative to the rectangular sample shape, with the diameter of the circle being the same width as the Calibrade® wheels are set apart (Figure 6.2).

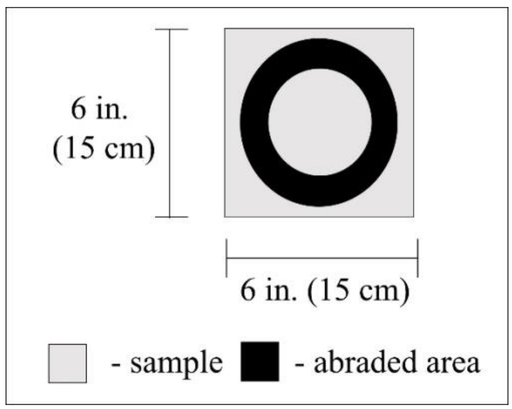


Figure 6.2. Abraded area for samples tested with Taber® abraser.

6.1.3. Cable Abrader

The cable abrader is a newly developed testing apparatus that utilizes stainless steel cable rope and brake tension to simulate the abrasive conditions created by a helicopter rescue hoist cable. The cable abrader is comprised of three main components: the simulated helicopter hoist system, the adjustable sample mount, and the attached monitoring software. Abrasion occurs when the sample mount is pressed to the tensioned hoist cable while it moves across the surface of the sample.

To mimic the conditions incurred by the helicopter hoist cable an identical cable has been mounted in the bidirectional reel system. The cable is 3/16-inch stainless steel wire rope, with a usable length of approximately 250 feet.

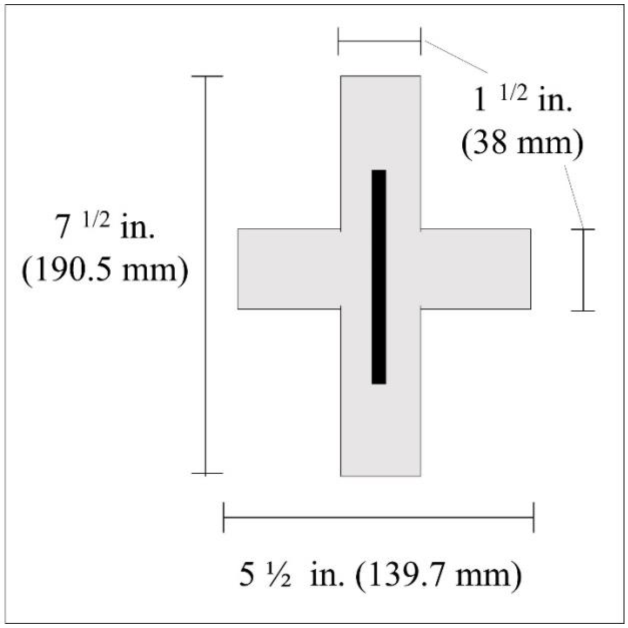


Figure 6.3. Abraded area for samples tested with the cable abrader apparatus.

6.2. Materials and Methods

6.2.1. Materials

Materials for this research was comprised of four categories: 2-layer laminated polyester SuperFabric™ base material, baseline leather, baseline gloves, and SuperFabric™ materials.

6.2.1.1. Selection of Materials

Materials for this research were a compilation of the materials listed in Chapter 4 and Chapter 5, all shown in Table 6.1. These materials included the two-layer laminated polyester base material (HBF), the baseline leather materials (BLA, BLB, BLC, BLD), the baseline gloves

(BLE, BLF, BLG, BLH), and the SuperFabric™ materials (SFA, SFB, SFC, SFD). All samples were tested on each abrasion test apparatus.

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Table 6.1. Reference chart of materials used for testing for cable abrader and Taber® abraser.

Type	Material Description	Average Thickness (mm)	Thickness Std. Dev. (mm)
HBF	two layered laminated polyester sheet	1.28	0.02
BLA	pig skin leather sheet	0.96	0.05
BLB	cow skin leather sheet, oil and water resistant	4.21	0.12
BLC	cow skin leather sheet, oil and water resistant	2.68	0.48
BLD	cow skin leather sheet, oil and water resistant	5.27	0.07
BLE	Hardy® glove, work style, padded leather	1.02	0.00
BLF	Lifesaving Systems Corp. ® hoist operator glove, leather	1.54	0.13
BLG	Priority 1® hoist operator glove, leather and Nomex	3.06	0.06
BLH	summer flyer style flight glove, leather and Nomex	1.35	0.02
SFA	single layer SuperFabric™ sheet, 600 denier, stormcloud grey color	1.04	0.01
SFB	two-layer SuperFabric™ sheet, 600 denier, mushroom color	1.56	0.01
SFC	two-layer SuperFabric™ sheet, 600 denier, hex grey color	1.55	0.02
SFD	single layer SuperFabric™ sheet, grey	0.66	0.00

6.2.2. Methods

Abrasion resistance was tested for baseline samples in accordance with Standard Guides for Abrasion Resistance of Textile Fabrics, ASTM D3884 (Rotary Platform, Double-Head Method/Taber®) and ASTM D4157 (Oscillatory Cylinder/Wyzenbeek) and the developed linear concentrated abrasion test method using the cable abrader. Data was gathered qualitatively as cycles to failure (visible hole in material).. The average cycles to material failure or stop are shown in the following sections, along with comparisons of the testing methods. After initial tests were performed, the data was compiled into averages, standard deviations and 95% confidence interval. JMP statistical software was also used to perform analysis of results.

6.3. Hypotheses

For this comparison between three abrasion tests, several hypotheses were developed. Because both the cable abrader's cable and the Wyzenbeek's screen abradant are both made with stainless-steel, the abrasion intensity should be similar, though the concentration of abrasion should be over a larger area for the Wyzenbeek. The Taber® abraser should have a similar concentration to the cable abrader, though the direction and shape should be different for the cable abrader apparatus. The cable abrader has the most similar conditions compared to hoist operations, so the abrasions incurred should be the most representative for any abrasion test method.

6.4. Results and Discussion

Data was collected for three abrasion test types: Wyzenbeek abrasion test, Taber® abrasion test, and cable abrasion test. Samples were evaluated based on the criteria outlined in each standard protocol, as well as visually compared for representation of hoist operation abrasive action observed in the field by operators.

6.4.1. Results

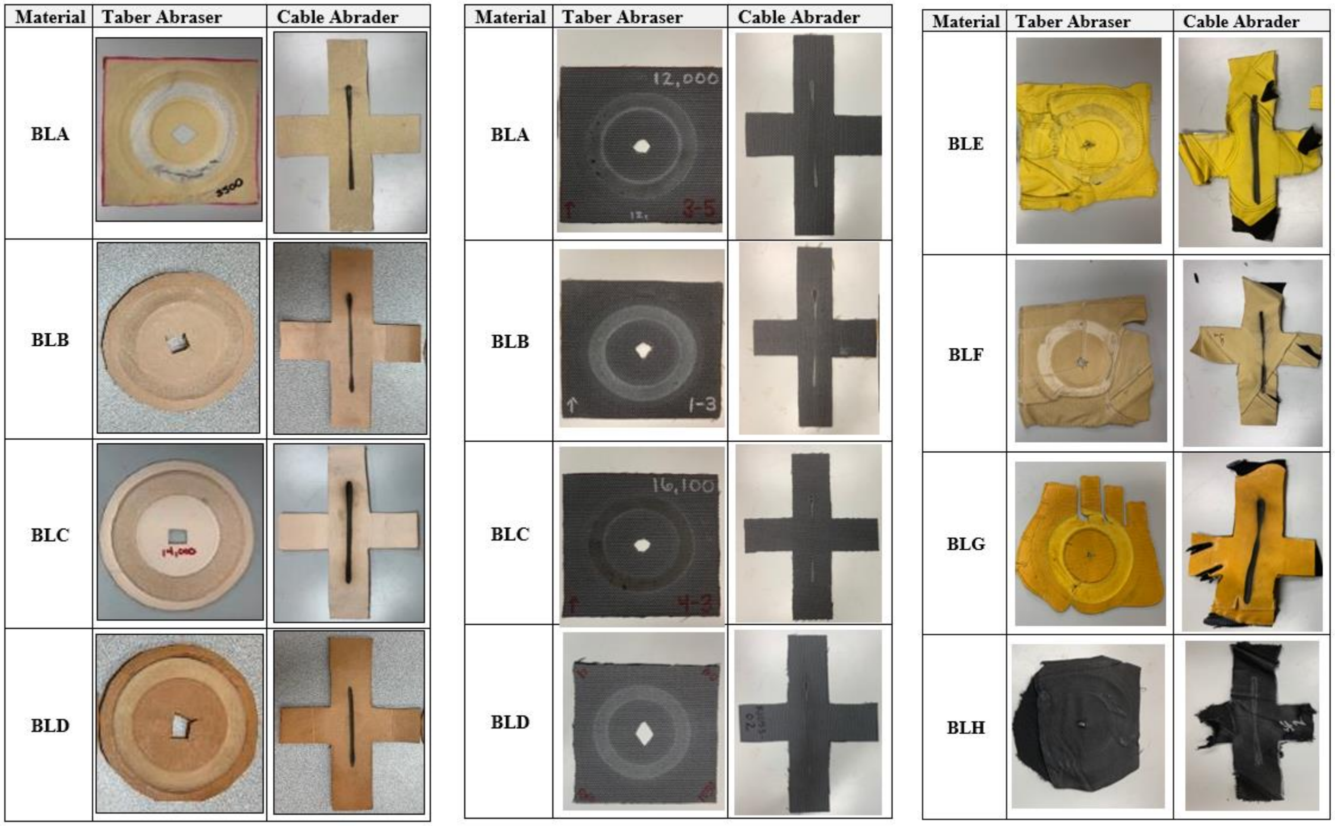

Figure 6.4. Comparison of results for Taber® abraser and cable abrader wear pattern.

6.4.2. Discussion

For rescue hoist operations, the wire cable rope produces a unique wear pattern that needs to be replicated to produce a realistic representation in a laboratory testing setting. For the Wyzenbeek abrasion tester, Flexing and Abrasion tester, and the Webbing abrasion tester the abrasion occurs in the center of the sample lengthwise and across the entire sample width. The Inflated Diaphragm tester and Martindale abrasion tester have the abrasive action in the center of the mounted sample, and the Taber® abraser has a circular pattern of abrasion in the center of the sample. Though the abrasion patterns appear similar between some of these methods, the application method for the abradant is different, resulting in different wear mechanisms. The sample is pulled taut across the abradant for the Flexing and Abrasion tester and Webbing abrasion tester, while the Wyzenbeek tester holds the sample still while rotating the abradant back and forth underneath. These different application styles result in different ratios of the sample area exposed to the abradant, and thus different levels of abrasion observed in terms of wear consistency. The Wyzenbeek tested samples wear in a gradient from the center of the length outward to the edges of the portion exposed to the abradant (Figure 3.2). The Webbing tester abrades samples more evenly across the wear area, whereas the Flexing and Abrasion tester wears closer to the center of the abraded area, with the material giving way or tearing at the weakest point in that portion. The Inflated Diaphragm and Martindale abrasion testers have similar sample shapes, but the method that the abradant is applied is different. The Martindale and Inflated Diaphragm testers also have a component on the other side of the sample from the abradant; the Martindale has a polyurethane backing foam to keep the sample taut, whereas the Inflated Diaphragm tester uses the inflated rubber diaphragm push the sample outwards; both of these methods produce even wear in those areas, with any material failure (hole in the fabric) occurring in that area. In a similar way to the Wyzenbeek tester, the Inflated Diaphragm sample is mounted at tension and the abradant is moved back and forth across the surface. The Taber® abraser wears in an even circular pattern as the sample is rotated on a platform under rolling abradant wheels, and material degradation or failure happens in that portion of the sample as well. In contrast to all of the aforementioned methods, it could be argued that the abradant (the stainless-steel cable wire rope) is moving while the material is held taut (during the initial Cable Down or return Cable Up, with little lateral cable movement), but also could be argued that the material is moving while the abradant is stationary (during more tumultuous motion with rescuers in tow, or with turbulence that the operator must compensate for). This shifting nature of the hoist's abrasive action provides a challenge in attempting a laboratory setting replication. The wear observed on hoist gloves was consistently in a pattern, with more frequent concentration in the hand pressure points. While the Wyzenbeek, Flexing and Abrasion, and Webbing abrasion testers all have relatively linear abrasions, none of the ASTM standard test methods have the narrow linear abrasion observed from the hoist cable. Even with the additional "linear abraser" add-on for the Taber® abraser, the abrasive head would still not produce the abrasion pattern caused by the wire rope cable.

Another characteristic working in conjunction with consistency to replicate hoist cable wear is abrasion intensity. The ASTM test methods for evaluating textile abrasion resistance have a fairly wide range of abrasive intensity due to the varied physical qualities of the tested materials and abradants. In this case, intensity means the amount of force and friction between the sample and the abradant. The Martindale tester uses the least amount of intensity in abrasion due to the relatively delicate materials tested, followed by the Inflated Diaphragm. The Webbing abrasion tester and the Flexing and Abrasion tester both have the sharp edge that the sample pulls against, but the wear is even across the entire exposed surface of the sample, as opposed to showing in the center like the hoist cable. The Taber® abraser appears to have the highest abrasion intensity capability out of the ASTM standard methods, with a maximum weight ranging from 1000 g to 4050 g. In terms of friction abrasion, the Taber® abraser also seems to be the most intense in terms of roughness with the Calibrade® wheels. While the Wyzenbeek has a stainless-steel screen abradant option that seems comparable to the stainless-steel wire rope cable, the uniformity of the screen does not have the same harshness on the sample surface as the hoist cable.

The concentration of material abrasion for the ASTM test methods mentioned also varies significantly between these methods. For the Taber ® abraser, the concentration is confined to the circle, but the pressure is spread out evenly along the Calibrade® wheels, in contrast to the cable abrader's pressure points on the sample face across the center.

With the all components necessary not being available in one specific abrasion test method, a modification or a completely new testing apparatus is needed to fill the gaps in replicating hoist cable abrasion. The hypotheses that were outlined to predict the behavior of the materials on the cable abrader, as well as see the differences between the cable abrader and the Taber® abraser. The measured parameters for the cable abrader are machine time to failure or stop, so comparing the different material types in terms of machine time can provide reinforcement for side-by-side comparison of those samples. If the SuperFabric™ is better than or equal to the baseline materials in terms of machine time to failure or stop, then the SuperFabric™ meets the requirement outlined by the Department of Homeland Security. If the SuperFabric™ is better than or equal to the baselines by thickness for cable abrader cycles to failure or abraded length to failure, then the gloves made with SuperFabric™ will have more flexibility without compromising the abrasion resistance. Understanding the correlation between material stiffness and abrasion resistance is important because of the potential linear relation between them; with a linear correlation the point of maximum abrasion resistance and minimum amount of material stiffness can be optimized for maximum material flexibility, and therefore, improved dexterity for the user. If the cable abrader shows to be equal to or better in terms of time to failure/machine run time and abraded length, then the use of the cable abrader in other testing could be justified.

6.5. Conclusions

Comparing the abraded length to failure for each is also a useful data set due to the ease of comparing cable abrader feet to actual helicopter hoist cable feet, resulting in a realistic calculation of material lifespan.

Materials tested on the cable abrader behaved in a way similar to how they would behave in a real hoist operation scenario. For material comparison, leather is abraded by stretching and pulling the material surface until the fibers give way and failure occurs, whereas SuperFabric® the abrasion occurs when the dot guard plate grinds down first, then a destruction of the base material fibers until material failure occurs. With performance showing equal to and greater than the leather on the cable abrader, SuperFabric™ shows to be a viable alternative to using leather, and could be implemented into hoist gloves without worry of fouling the cable. When evaluating materials for hoist gloves, the cable abrader is superior to the Taber® abraser due to the combination of repeatability of testing and realism to the actual hoist operation conditions. Machine time and abraded length are useful ways to compare Taber® abraser cycles with the cable abrader cycles to understand the abrasion resistance of a material. Abrasion test methods are unique in their mechanism of abrasion and the intensity of the abradant. In considering testing that could be analogous to rescue hoist operations, the Wyzenbeek abrasion tester did not have the intensity required to successfully represent the concentrated abrasion pattern incurred from the helicopter hoist cable, even though the stainless-steel screen and wire rope have similar compositions. The Wyzenbeek abrasion tester was also insufficient in terms of abrading the SuperFabric™ materials, as with similar testing times for the Taber® and cable abraders produced failure in the same material types. The Taber® abraser relies on the weight on top of the coarse Calibrade® wheels for the constant intensity needed to break through materials. However, increasing the weight on the Taber® abraser would not necessarily provide more comparable results due to the difference in abrasion mechanism. Similarly, the cable abrader maintains constant relative pressure on the sample for the entire length of the cable wire rope.

CHAPTER 7 . CONCLUSIONS AND RECOMMENDATIONS

7.1. Test Development Conclusions

The cable abrader is a viable test method to appraise the abrasion resistance of materials in a simulated scenario for hoist operations. The red silicone sample mount backing works to quickly and easily identify material failure on the cable abrader apparatus and would be helpful in future iterations of the apparatus. Through statistical analysis the average speed shows to be 93-98 feet per minute, with a practical cable deflection between 0.5 and 1.125 inches. The repeatability and versatility of settings for the cable abrader were proven effective for abrasive conditions and sample testing behavior. The linear concentrated abrasion test method using the cable abrader is a novel approach to testing the durability of materials with a focus on application and end-use.

Consistency of cable runs can be maximized by keeping the sample set pressure and cable deflection as close to the same values as possible. The inconsistent ability to attain similar sample pressure or cable deflection can be indicative of needing to perform maintenance on the brake system. The monitored parameters during a cable abrasion test run are consistent across all five samples and any variations found in the sample data are most likely from properties of the two-layer laminated polyester material. The speed of the cable abrader is slightly different depending on the cable direction, but did not affect the data and using five samples per test is an adequate number to see any effect that might come from the material. Variation and inconsistencies for the abraded length and machine run time are due to the newness of the apparatus and human error, which was addressed and corrected, but could be improved with a stopping mechanism.

Measured parameters for the linear concentrated abrasion test method are reasonably consistent in terms of abrasion resistance and operating conditions. When operating cable abrader runs, there was a difference in the running conditions between cable up and cable down due to the construction of the machine or placement of the brakes.

The abrasion pattern for the cable abrader is linear and vertically positioned across the center of the sample, with pressure points at the top and bottom of the sample mount area, and the point of material failure at the top position.

Overall the linear concentrated abrasion test method is consistent, therefore any variations during testing of samples will be due to the properties of that material and not from variability in the cable abrader testing. The reliable platform that the linear concentrated abrasion test method provides allows for an accurate representation of the abrasive conditions encountered during hoist operations with the repeatability and consistency of a laboratory setting.

7.2. Material Comparison Conclusions

The linear concentrated abrasion test method using the cable abrader is a reliable, repeatable abrasion test procedure for qualifying prototype materials. Using the cable abrader for comparing material types allows for an accurate comparison of materials in both material longevity for sample type, as well as material averages against one another. The leather materials were a good representation of the baseline gloves, and allowed for a material level comparison between fabric types for eventual prototypes. This closeness in durability and abrasion resistance provided more flexibility when testing the durability of materials, specifically when glove scarcity was an issue. The SuperFabric® performed the best out of the materials by thickness and machine time for abrasion.

7.3. Test Method Comparison Conclusions

Materials tested on the cable abrader behaved in a way similar to how they would behave in a real hoist operation scenario. For material comparison, leather is abraded by stretching and pulling the material surface until the fibers give way and failure occurs, whereas with SuperFabric™ the abrasion happens by the dot guard plate grinding down first, then a destruction of the base material fibers until material failure occurs. With performance showing equal to and greater than the leather on the cable abrader, SuperFabric™ shows to be a viable alternative to using leather, and could be implemented into hoist gloves decreasing likelihood of fouling the cable. In terms of evaluating materials for hoist gloves, the cable abrader is superior to the Taber® abraser due to the combination of repeatability of testing and realism to the actual hoist operation conditions. Machine time and abraded length are useful ways to compare Taber® abraser cycles with the cable abrader cycles to understand the abrasion resistance of a material. Abrasion test methods are unique in terms of the mechanism of abrasion and the intensity of the abradant.

For helicopter hoist operations, current abrasion test methods do not offer the conditions necessary for replication. The Wyzenbeek abrasion machine had an abradant with a similar base composition as the hoist cable, using a stainless-steel screen, but ultimately had softer, wider abrasion than would work with the SuperFabric®. The Taber® abraser showed a similar material failure profile as the cable abrader, though the actual time to failure for machine was far greater for the Taber® abraser. Similarly, the cable abrader maintains constant relative pressure on the sample for the entire length of the cable wire rope. With the correct representative pressure and intensity of the abrasions for helicopter hoist operations, the cable abrader showed to be the best option overall.

7.4. Recommendations

There are several recommendations for future iterations of the linear concentrated abrasion apparatus and testing process.

For the cable abrader apparatus, a cable feeder system or reel grooves should be added to allow the cable to wind neatly would allow for a longer life of the cable and much less variation in terms of the pressure experienced by the sample. Another consideration that would be useful would be an automatic gear switch for switching between cable up and cable down. For one complete cable abrader cycle the machine run time would be around five and one-half minutes, with another one to two minutes of time spent switching back and forth to the other gear and setting everything for that run. A gear switch mechanism or a fully automated system to coordinate with the cable direction settings that need to be set before a cable run, the complete time working with the cable abrader will turn into the lean machine run time.

Another addition to the cable abrader apparatus that would be immensely useful is an onboard tachometer that hooks in with the software system. The speed in real time terms could also be useful in determining the point of material failure eventually.

Sample mounting could also be improved in several ways. More elastic straps for the hook and loop system for the top and bottom of the sample mount would be useful for more stiff materials that still need to be mounted and abraded. Also, the sample mount area in general could be improved by making it generally more accessible. One option that might work well is to modify the bars that the sample mount and load cell are mounted to by changing it to a moving platform that can tilt over to the side or facing upwards in order to easily see the sample without having to use the actuator handle to move it backwards slowly.

Monitoring the abrasion of samples could be improved significantly by having a mounted camera or video system aimed at the sample area. This could allow for real time observation of sample changes, while also monitoring the condition of cable as well.

7.5. Future Work

Future work related to the linear concentrated abrasion test method and the cable abrader could include testing different glove types, using different cable materials, studying degradation of the cable wire rope, and employing the wet sample testing component.

Glove types other than hoist operator gloves could benefit from abrasion testing using the cable abrader. In a similar line as the hoist operator glove, the cable abrader could also test for rappelling gear related to rescue helicopter operations at a higher pressure and faster cable run speed. Outdoor recreation activities such as rock climbing that employ protective gloves could also improve the abrasion resistance without compromising dexterity by using the cable abrader to test prototypes. The agriculture industry has countless uses in testing work gloves used in livestock rearing or sheep shearing where the wearer needs to have dexterity without compromising on the abrasion resistance. Testing glove materials with the cable abrader could allow for the further development of useful products.

Another opportunity related to the cable abrader apparatus is adding the ability to switch out the stainless-steel cable wire rope out for different materials to mimic various abrasions. Furthermore, it could be that lineman that work on power lines have to deal with a different size cable and conditions but could benefit from a better glove. Recreational extreme sports participants for bungee jumping or zip lining could benefit from understanding the wear pattern of the materials they wear in relation to the cable they use. The cable abrader could also be a unique way to test the abrasion behavior of the different cables themselves.

Understanding the degradation of the stainless-steel cable wire rope would also be interesting and important to research. After researching potential issues with the cable during use (unravelling, birdcaging, breaking, welding), there could always be useful information gathered from monitoring the degradation time for the cable. This information could also help prevent further issues with hoist cables in the future.

Though the work done with the cable abrader and the linear concentrated abrasion test method is applicable due to the simulation of hoist cable operation, further research on testing should be pursued in order for wet conditions to accurately simulate the real conditions for the responders different in climates and geographical locations.

CHAPTER 8 . REFERENCES

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APPENDICES

APPENDIX A: CABLE ABRADER STANDARD OPERATING PROCEDURE

1. Flip power switch to "ON", see Figure A.1.
2. Turn computer on. Make sure software is running and that load cell is reading.
3. Determine direction cable needs to go. (If the reel closest to the sample mount is full, it will be going in the Cable Up direction. If the reel farthest away from the sample mount is full, it will be going in the Cable Down direction.)
4. Manually set gear selection to drive in desired direction. (Cable Up position is closest to the cable reels, Cable Down is closest to the access door. Neutral is in between both locked in settings, as seen in Figure A.2)
5. Turn Brake Power switch to ON position as seen in Figure A.3.
6. Set brake direction on switch panel as seen in Figure A.4
7. Turn on motor power switch on speed control panel to forward position (RUN CCW), as seen in Figure A.5, then slowly turn the speed control to add tension to the cable.
8. Place sample on sample mount area, tucking top and bottom under the hook and loop straps, and tucking sides through the side clamps, tightening with wingnuts, and being careful to keep the sample as flat to the sample mount area as is possible. (Seen in Figure A.6).
9. Set sample pressure by using small actuator handle at back of sample mount to move sample towards the cable, aiming for a sample pressure of 10.0 +/- 0.5 ftlb.
10. Turn on motor (UN CCW setting) and start timer.

    a. Let cable run for ~250 ft, monitor via attached measuring wheel.

    b. Make sure reel keeps approximately 7 wraps of cable at least.

11. Stop motor by flipping switch back to neutral position and stop timer.

12. Remove tension on sample by using crank to move sample away from the cable.

13. Check sample visually, take pictures to monitor progress.

14. Flip brake power switch to OFF.

15. Manually set gear selection to drive in opposite direction.

16. Flip brake power switch to ON.

17. Set correct brake direction on switch panel and move sample mount to correct position with side actuator handle. (see Figure A.7) and then set the rolling tape measure set at the top of the cable perpendicular to the sample.

18. Turn speed knob very slowly to add tension to cable.

19. Set sample pressure again to 10 +/- 0.5 ftlb.

20. Repeat steps 9-19 until inspection of sample indicates material failure (visible hole appears in material, and the red portion of the sample mount is visible. See Figure A.8 for an example of a material at the failure point).

Figure A.1 Control box showing power switch

Figure A.2 Manual gear positioning – Cable Up (left), neutral (center), Cable Down (right).

Figure A.3. Control box showing power switch.

Figure A.4. Control box showing brake direction switch.

Figure A.5. Speed control panel with motor power (circle) and speed knob (square).

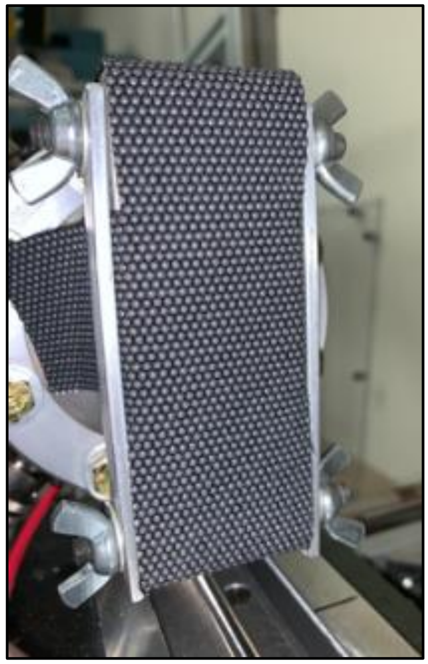

Figure A.6. Front view of mounted sample on cable abrader sample mount.

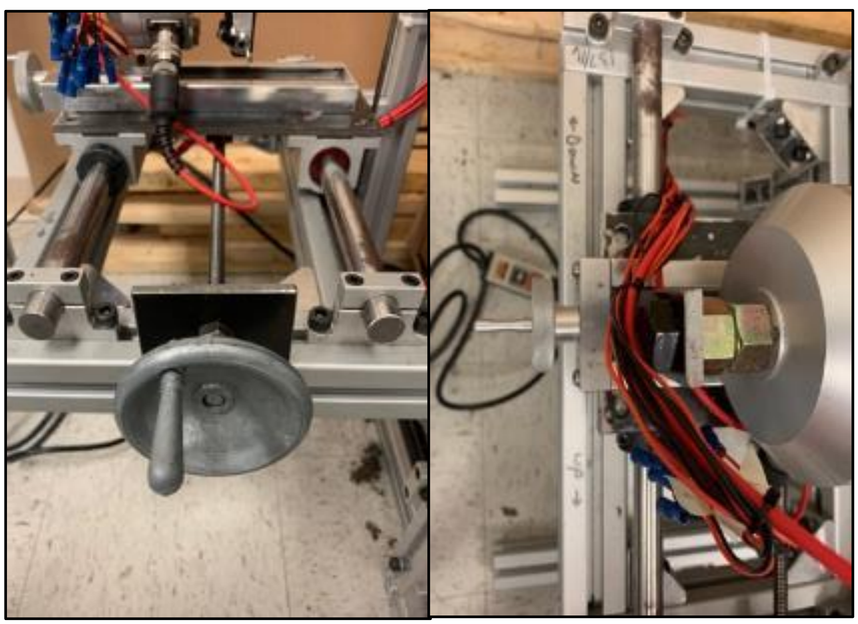

Figure A.7. Handle to move sample mount position, direction indicator marks for setting sample mount using actuator handle.

Figure A.8. Front view of sample at failure point with red sample mount showing through material on cable abrader.

APPENDIX B. CABLE RUN DATA RECORD SHEET TEMPLATE

Sample:	Sample:	Sample:	Sample:
Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):
Time:	Time:	Time:	Time:
Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):
Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb
Top:	Top:	Top:	Top:
Bottom	Bottom	Bottom	Bottom
Inst. Speed:	Inst. Speed:	Inst. Speed:	Inst. Speed:
median pressure:	median pressure:	median pressure:	median pressure:
Sample:	Sample:	Sample:	Sample:
Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):
Time:	Time:	Time:	Time:
Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):
Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb
Top:	Top:	Top:	Top:
Bottom	Bottom	Bottom	Bottom
Inst. Speed:	Inst. Speed:	Inst. Speed:	Inst. Speed:
median pressure:	median pressure:	median pressure:	median pressure:
Sample:	Sample:	Sample:	Sample:
Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):
Time:	Time:	Time:	Time:
Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):
Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb
Top:	Top:	Top:	Top:
Bottom	Bottom	Bottom	Bottom
Inst. Speed:	Inst. Speed:	Inst. Speed:	Inst. Speed:
median pressure:	median pressure:	median pressure:	median pressure:
Sample:	Sample:	Sample:	Sample:
Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):	Run #: Abraded Cable Length (ft):
Time:	Time:	Time:	Time:
Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):	Observed Sample Pressure Range (ftlb):
Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb	Deflection (in): 5ftlb 10 ftlb
Top:	Top:	Top:	Top:
Bottom	Bottom	Bottom	Bottom
Inst. Speed:	Inst. Speed:	Inst. Speed:	Inst. Speed:
median pressure:	median pressure:	median pressure:	median pressure:

APPENDIX C: CABLE ABRADER AND TABER® COMPARISON DATA

	CA CTF	CA CTF StDev	Taber® CTF	Taber® CTF StDev
BLA	1.60	0.42	3691.00	1171.33
BLB	30.10	0.03	50000.00	0.00
BLC	30.77	1.43	46562.60	37651.93
BLD	30.05	0.03	60000.00	22360.68
BLE	7.68	2.53	1566.67	230.94
BLF	12.03	1.02	2750.00	661.44
BLG	23.39	2.07	14433.33	13740.94
BLH	3.51	0.50	351.00	258.08
SFA	16.90	7.04	12700.00	4216.63
SFB	28.29	0.26	20080.00	9924.31
SFC	34.69	1.58	74320.00	29552.28
SFD	7.57	3.80	50000.00	0.00