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DEVELOPMENT OF A TEST METHOD TO EVALUATE TEXTILE WEAR RESISTANCE

by
Margaret A. Auerbach
Jeffrey R. Faulkner
Gary N. Proulx
and
Michael F. Coyne

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U.S. Army Combat Capabilities Development Command Soldier Center
Natick, Massachusetts 01760-5000

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14. ABSTRACT
The oscillating motion of the new test apparatus development under this work effort, when combined with an abrasive media, produces a large (15″x15″) uniformly abraded material. The abraded material, can then be cut into several test specimens to characterize and provide a quantifiable means of evaluating the physical properties (tensile strength, tear strength etc.) and performance of the abraded fabric by comparing it directly to unabraded fabrics and/or other fabrics to aid in downselecting the best material. The versatility of the tester allows it to accommodate a wide variety of materials as well as abrasive media in order to simulate various environmental and/or operational conditions. The use of ceramic bevels or "synthetic rocks" (to simulate an urban or subterranean environment) were found to be an effective media in abrading standard textile fabrics. Three fabrics (ACU, FRACU and A2CU) were subjected to a limited amount of timed abrasion tests ranging from 30-360 min. All three fabrics exhibited significant changes in their warp tensile strength properties after 30 min of testing and continued to degrade through the 360 min tested. This testing suggests that a visual evaluation of abraded material after testing, or using a rupture in fabric yarns or hole formation as the fabric's end point is not an adequate assessment of the abrasion resistance of the fabric or the effect of abrasion on the fabric's performance. The large uniformly abraded area produced during this testing provides a unique advantage over other abrasion testers and provides the opportunity to quantifiably assess the performance of abraded fabrics, a capability which previously did not exist.

15. SUBJECT TERMS

ACU	DURABILITY	ABRASION MEDIA	TEST AND EVALUATION
A2CU	PROTECTION	HOLE FORMATION	ACU TENSILE PROPERTIES
SAND	OSCILLATING	TENSILE STRENGTH	PROTECTIVE EQUIPMENT
DUST	DEGRADATION	BREAKING STRENGTH	SAND ABRASION TESTING
FRACU	TEST METHODS	ABRASION EQUIPMENT	CERAMIC DEBURRING MEDIA
FABRICS	SAND ABRADER	ABRASION RESISTANCE	PERFORMANCE(ENGINEERING)
TEXTILES	TEAR STRENGTH	PROTECTIVE EYEWEAR	ACU(ARMY COMBAT UNIFORM)
ABRASION	ABRASION TESTS	A2CU(ARMY AIRCREW COMBAT UNIFORM)	
VIBRATION	ORBITAL SHAKER	FRACU(FLAME RESISTANT ARMY COMBAT UNIFORM)	

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Preface

The work reported was performed by The US Army Combat Capabilities Development Command Soldier Center (DEVCOM SC) under project 18-314 Test Method to Evaluate Textile Wear Resistance and funded under the Susceptibility Thrust Area from October 2017 – September 2020. The proposed program was to develop a new laboratory test to evaluate the wear resistance of textile materials and validate laboratory abrasion testing against actual field wear. After conducting laboratory testing, abraded fabrics were to be compared to fabrics taken from garments after 6 months and one year of wear in the field. Field wear test was being conducted under a separate work effort, 18-304 Test Method for Assessment of Durability of Textile Materials. Abrasion was a small portion of this larger work effort. Testing was focused on the ACU (50% Nylon/50% Cotton- NYCO fabric).

Due to the lack of abrasion evident on Army Combat Uniforms (ACU) received from field testing, it was not possible to develop a rating system that would correlate laboratory testing to abraded garments worn in the field. In October 2019, after weighing several options, a decision was made to abrade standard uniform fabrics to determine proof of concept for the test method developed rather than redirect program funds towards additional field testing. 18-304 ended in FY 19 and received no further funding.

While there is currently no program to continue this development effort, the equipment developed can be used in future studies to correlate laboratory abrasion testing to field wear and/or to determine the useful life or performance of fabrics, coatings and finishes after abrasion testing. The large uniformly abraded area obtained using this new abrasion tester provides a unique advantage over other abrasion testers. Abraded fabrics can now be cut into standard textile specimen sizes to characterize their physical properties (tensile strength, tear strength etc.) and a quantifiable assessment of their performance can be obtained providing a capability that previously did not exist.

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The authors would like to express appreciation to Ms. Susan Gassett for her assistance in interpreting ASTM D5034 and ASTM D4632 test methodologies and data and Dr. Judith Sennett for compiling Appendix A.

DEVELOPMENT OF A TEST METHOD TO EVALUATE TEXTILE WEAR RESISTANCE

1 Introduction

The work reported was performed by The US Army Combat Capabilities Development Command Soldier Center (DEVCOM SC) under project 18-314 Test Method to Evaluate Textile Wear Resistance and funded under the Susceptibility Thrust Area from October 2017 – September 2020.

The need for validating laboratory abrasion testing against actual field wear has been recognized for many years. Abrasion is considered the single most important factor in wear. Literature clearly demonstrates that laboratory equipment with an abrasive type action most closely resembles the type of wear seen in actual field wear. In the late 60s, a considerable amount of work was done on evaluating the wear properties of a number of materials, including natural and man-made fiber blends such as 50/50 nylon/cotton (NYCO). After evaluating standard abrasion testing methods in use at that time – Stoll, Taber, BFT Mark III Abrader, Wyzenbeek etc., two new abrasion instruments were developed, which were referred to as the Sand Abrader and the Sand Blast Tester [1,2]. Testing indicated both the Sand Abrader and Sand Blast Tester provided a reasonable degree of assurance in predicting the relative ranking of fabrics subjected to field wear of an abrasive type. After much research, it appears neither test was developed into a standard test method. The intent of this work effort was to leverage previous work to develop new and improved versions of these test systems and to validate testing comparing laboratory testing to actual field testing. While textile options have certainly expanded since the 60s and there are many more fibers and blends now available on the market and used in uniform systems, the lack of correlation between laboratory data and actual field wear still exists.

1.1 *Sand Abrader and Sand Blast Tester*

Earlier research with the sand abraders mentioned above determined that abrasion resulted when the sand penetrated the fabric surface causing fiber/fabric damage. This damage could be in the form of fiber fibrillation, or in the formation of holes, tears, or frayed fabric areas. Three factors were identified that affected the rate and extent of abrasion:

1. the interface between the fiber and abrading material
2. the external loading condition
3. the energy absorbing ability of the fibers [1]

In the sand abrader, the fabric oscillated back and forth over a sand–block combination and the end point of the test was determined by the number of cycles required to form a hole. In the sand blast tester, a pressurized stream of sand was directed at a clamped fabric until a hole was formed.

In these past studies, both the sand abrader and sand blast tester predicted a reasonable ranking of fabrics when comparing fabrics subjected to cycles (sand abrader) or seconds (sand blast tester) to fabrics from actual garments worn in the field with the aid of a rating system developed specifically to correlate swatch level laboratory testing to a field tested garment. See Table 1. In the subject work effort, the rating system used in earlier testing was to be updated and modified accordingly to accommodate the increased volume of man-made and blended fabrics currently being used in the Soldiers' clothing items. The resulting abrasion characteristics may or may not be similar to previously tested fabrics. The scoring system was to be used to score garments at different selection points identified in field testing being conducted under a separate work effort, 18-304 Test Method for Assessment of Durability of Textile Materials. Most textile specifications do not cite abrasion requirements due to their subjective nature and there is some reluctance to quantify this property; however, this new test method may sufficiently quantify abrasion parameters to allow inclusion of this characteristic in future material specifications.

Table 1. Scoring System for Worn Garments [3]

Type of Failure	Degree					
	1	2	3	4	5	6
Holes (diameter-inches)	$\leq$ 0.25	> 0.25 $\leq$ 0.5	> 0.5 $\leq$1.0	> 1.0 $\leq$1.5	> 1.5 $\leq$2.0	>2.0
Tears in wear area* (length - inches)	$\leq$ 1.0	> 1.0 $\leq$ 2.0	> 2.0 $\leq$3.0	>3.0 $\leq$5.0	> 5.0 $\leq$ 7.0	>7.0
Frays (length - inches)	$\leq$ 1.0	> 1.0 $\leq$ 3.0	>3.0 $\leq$6.0	>6.0 $\leq$10.0	> 10.0 $\leq$ 15.0	>15.0
Wear areas (sq inches)	$\leq$ 4.0	> 4.0 $\leq$ 9.0	> 9.0 $\leq$16.0	> 16.0 $\leq$ 25.0	> 25.0 $\leq$ 36.0	>36.0
Points Scored						
Holes	5	9	11	13	14	15
Tears in wear area	5	9	11	13	14	15
Frays	0.5	1	2	3	4	5
Wear Areas	4	6	9	11	13	15

2 Methodology

2.1 *Development of Test Apparatus*

At the beginning of this work effort, a literature search was conducted to identify the abrasion test methods, equipment, abrasion media, sample sizes and assessment methods currently in use to evaluate the abrasion resistance of textiles. A summary of this information can be found in Appendix A.

After evaluating current test methods, two concepts were developed and considered for development of a new test fixture to evaluate the abrasion properties of fabrics. The higher risk concept involved moving the fabric both back and forth and side to side over an abrasive material mounted on a rotating cylinder, allowing even surface abrasion wear in multi-axis motions over a large surface area. See Figure 1. After encountering many challenges and reevaluating the complexity and feasibility of this design, it was determined this system would not provide any significant differences in abrasion than the simpler orbital shaker abrasion test (the lower risk and initial concept design) which had been developed first under this work effort and was already in use providing abrasion data when the second concept was abandoned. This tester will be discussed next.

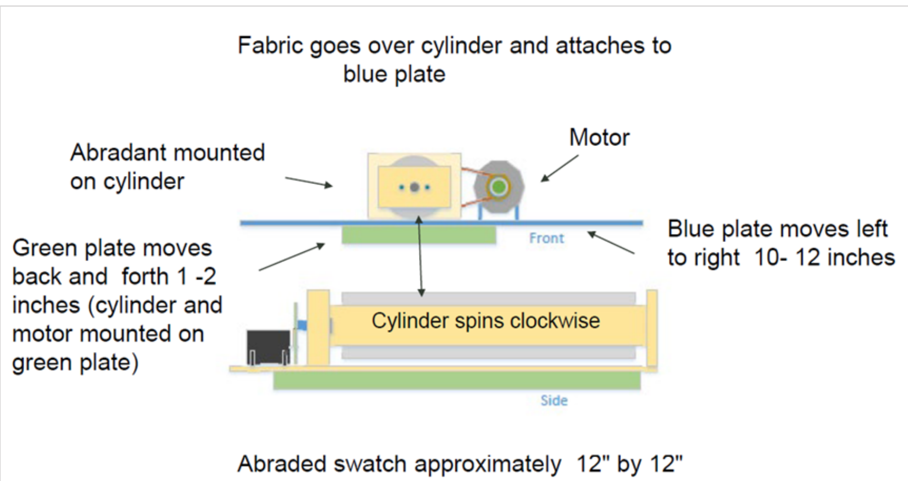


Figure 1. High Risk Prototype Design

2.2 *Prototype Concept*

Based on the information above, the lower risk design, which involved modifying a commercially available orbital shaker, was pursued. The final design is a modified version of orbital shaker, Orbi Shaker™ XL, manufacturer Benchmark Scientific, Part No: BT1010, 30-300 rpm, 5 x 18.5 x 21.25" with a non-slip (green) silicone mat platform (see Figure 2). A guard with cam handles was added around the edges of the plate to secure samples during testing. Later, the cam handles were replaced by nuts to allow a quicker, easier way of switching samples for testing. This new test equipment provides a unique capability in that it is able to abrade a large surface area (15 ″x15″), far larger than any textile abrasion test equipment currently in existence (See Appendix A). The vibrating/shaking motion of the test apparatus abrades the fabric in a circular 19 mm orbit, uniformly abrading the fabric, which can then be cut into standard textile specimen sizes to characterize the physical properties (tensile strength, tear strength etc.) of the abraded fabric and directly compare it to non-abraded fabrics or other fabrics to aid in down selecting the best materials. The versatility of the tester allows it to accommodate a wide variety of materials as well as abrasive media in order to simulate various environmental and/or operational conditions.

a.

b.

Equipment Size:
3 ft x 3 ft x 3 ft
Sample Size:
16 in x 16 in
Abraded Area:
15 in x 15 in

Figure 2. Low Risk Prototype Design—Modified Oscillating Table with Green Silicone Mat. a. Front view; b. side view

After running initial proof of concept testing with fabric swatches, modifications were made to the test apparatus. A plexiglass enclosure containing four fans and an air filter was built to encase the test fixture (see Figure 3). This modification allowed visual observation of the testing while safely containing the dust/lint generated during testing. One fan was placed on each side of the unit— two smaller fans were positioned on opposite sides of one another, and two larger fans were positioned on the remaining sides of the fixture. A filter was attached to one of the larger fans. Each set of fans was run off separate power supplies. The filter system was capable of collecting lint/dust down to 2 µm. See Appendix B for a complete/detailed list of parts used to construct the equipment.

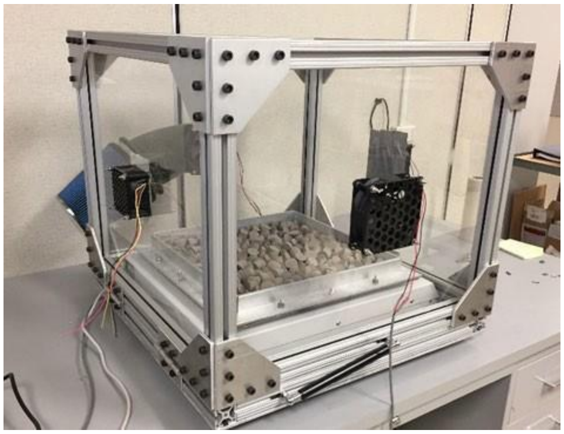
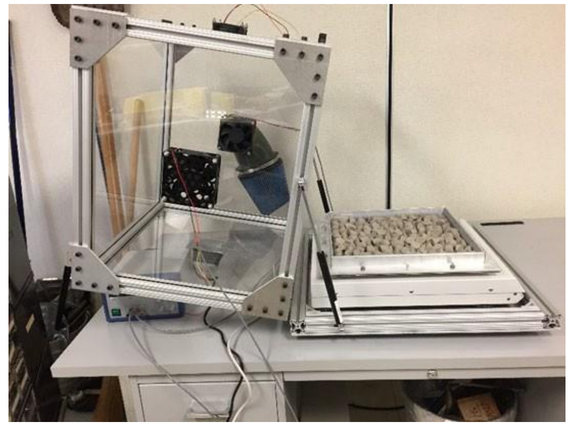
a.  b. 

Figure 3. Final Abrasion Tester with Hood and Dust System (Power Supplies Not Shown). a. Closed; b. Open

2.3 *Abrasion Media*

2.3.1 Sand

Leveraging experience that was gained during the development of a Blown Sand Abrader used for eyewear testing in the early 2000s [4], it was determined that sand may not be the best material to use for abrasion. The Blown Sand Abrader Test Method was designed to replicate eyewear damage resulting from blowing sand in desert environments. This test was specifically designed to simulate sandstorm damage and the quartz silica used in the test is equivalent to the hardest desert sand particles (hardness of 7 Moh), delivered to the eyewear/lens at a velocity of 16.5 m/s. The use of sand, however, presents some testing and health challenges as listed below:

1. Inhalation exposure to free silica may cause delayed lung injury, including silicosis, a disabling and potentially fatal lung disease, and/or cause or aggravate other lung diseases or conditions.
2. Free silica is classified as a known human carcinogen. [4]
3. There are many different types of sand with varying compositions, hardness and particle diameters. In addition, sand must be stored at the proper temperature and relative humidity to prevent clumping and ensure proper dispersion in testing.

While blowing sand may be effective in determining the abrasion resistance of eyewear coatings, other suitable materials were explored for abrasion of textiles to simulate garment field wear. Future conflicts are predicted to be in urban, subterranean and/or cold weather environments; therefore, sand may not be an appropriate media to determine the durability of coatings and/or materials under these environmental conditions. The versatility of the test method under development and the ability to change the abrasive material (for example concrete, dirt, gravel, or sand) based on the environmental conditions and operational environment supports the Army's Modernization efforts with regard to Soldier Lethality and Synthetic Training Environment (Cross Functional Teams); and the concept a Multi-Domain Operations (MDO) Capable Force in 2028 and a MDO Ready Force in 2035.

2.3.2 Rocks

Rocks were the first abrasion material utilized. They were readily available and seemed more appropriate than sand to simulate the field wear Soldiers may be exposed to in an urban or subterranean environment such as granite structures, underground bunkers, underground tunnels and subway systems [5].

Two different types of rocks (gravel) approximately 0.75″-1″ in size were found on the installation and collected for use in testing, as shown in Figure 4. The first tests were run using gravel found in a parking area on the installation. Because this gravel was found in a heavily used area, the rocks had a smooth, rounded surface. Additional testing was conducted using gravel found under a trailer, which was undisturbed. These rocks had a rougher surface appearance. All gravel was washed and sorted to remove any dirt or foreign materials that could affect test results. Rocks that were flat, oddly shaped, too large or too small were removed so all rocks were around the same size, shape, type and material.

Based on preliminary testing, it was determined that the rocks (gravel) would need to be replaced after each test going forward. These rocks worked well, but both sets appeared to wear down quickly and easily as indicated visually with a smoother surface appearance after testing. The rocks (gravel) also created a lot of dust during testing.

a.

b.

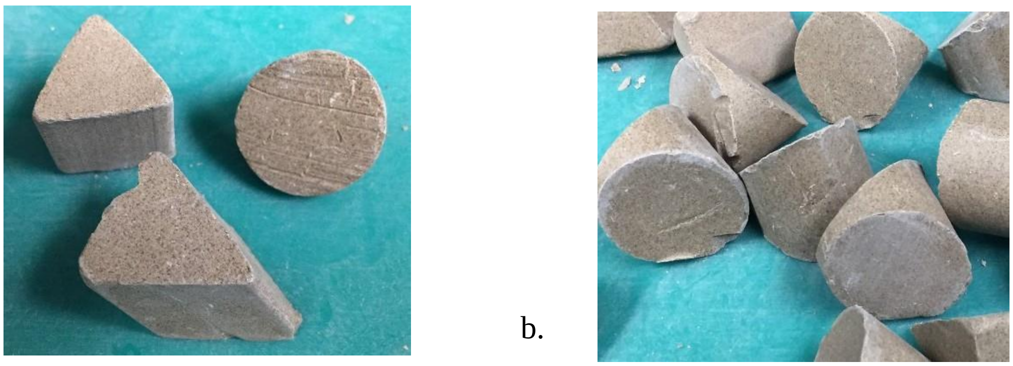
Figure 4. Rocks a. Rounded Edges; b. Rough Edges

2.3.3 Ceramic Deburring Abrasive Media (“Synthetic Rocks”)

A commercially available ceramic deburring abrasive media similar in size and shape to the rocks previously used in testing was identified and utilized in subsequent testing. These ceramic “rocks” were expected to last significantly longer than the gravel previously used without breaking down, which would therefore improve the reliability of the testing process as the abrasion cycles increased in number. (These synthetic rocks may have an added advantage – it may be possible to recondition them by running the media against “an abrasive grain occasionally to roughen the surface and clean the pores”, thereby extending their lifecycle in abrasion testing [6].)

A ceramic 1” BV Wedge abrasion media used for deburring and resembling the size and toughness of gravel “rocks” was purchased from Giant Finishing Inc.

(https://giantfinishing.com/media/ceramic/) in three different shapes and configurations as pictured in Figure 5. After mixing different combinations of the three shapes and observing how they interacted with one another on the modified orbital shaker at 300 rpm, it was determined the bevel-shaped ceramic wedges would be used solely on the basis of the movement observed. Counter to what was originally expected, the mixing of different shapes resulted in them locking together and scuffing back and forth instead of tumbling and rolling on the test surface. The selected shape provided the best tumble and roll action in the test conditions identified. These will be referred to as “synthetic rocks” throughout the report.



a. b.

Figure 5. Ceramic Deburring Media "Synthetic Rocks". a. Shapes Considered; b. Bevel Wedge "Synthetic Rocks" Selected for Abrasion Testing

3 Abrasion Testing

3.1 *Preliminary Testing - Proof of Concept*

Preliminary tests were conducted on two experimental FR fabrics—one a modacrylic blend and the other a 100% treated FR Cotton—which were used in previous CO_2 laser testing [7]. Photos can be found in Figure 6, and details on these fabrics can be found in Table 2. Fabric test panels (16″x 16″) were cut and secured on the oscillating plate, the surface was covered with one layer of rocks packed sufficiently to allow movement and the equipment was run at 300 rpm for 60, 90, and 120 min respectively. To verify the rocks were actually making contact with the fabric surface, one rock was painted black to track its movement. The rock successfully made its way along the surface of the fabric indicating the rocks were being tumbled and rolled, making contact at multiple points along the fabric surface. The same rocks were used for each fabric test set—three tests run at 60, 90 and 120 min—270 min or 4½ hours of total run time for each group of rocks used. The rounded rock "gravel" found in the heavily used area with smooth rounded surfaces were used when testing the Tecasafe Plus 700 (modacrylic blend) khaki fabric and the rougher rock "gravel" found under a trailer undisturbed were used in testing the Westex Indura (FR cotton) navy fabric.

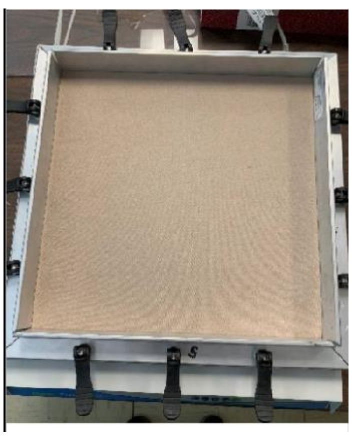
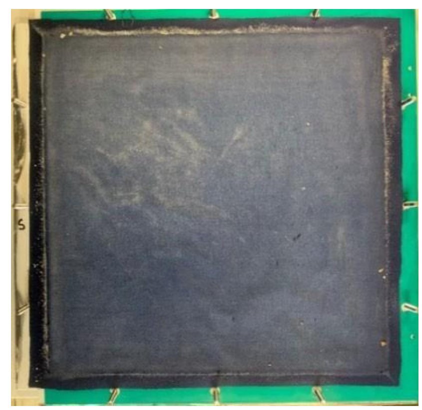
a.  b.  c. 

Figure 6. Preliminary Testing a. Fabric Mounted in Frame; b. Modacrylic Blend Abraded 60 min, Frame Removed; c. FR Cotton 60 min, Frame Removed

Four (4 in x 8 in) samples were cut from each abraded test sample from the warp and fill direction to conduct breaking strength tests in accordance with ASTM D 4632 Standard Test Method for Grab Breaking Load and Elongation of Geotextiles, which is comparable to ASTM D5034 Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test). Non-abraded control samples were also cut and tested. Test results indicated the material was in fact losing strength, with the greatest loss in breaking strength seen after 60 min of testing. See Figure 7. Based on this preliminary testing, it was concluded that the test effectively abraded the fabric samples and the effect of abrasion on the tensile properties of the fabric could be quantified by test data. The biggest variable in the test was the abrasion media used—the rocks. They degraded during testing and gave off an excessive amount of dust, which could be hazardous to one's health. Based on these findings, modifications were made to the equipment design to include a portable hood with a dust collection system, which consisted of four fans and a 2 µm filter (as discussed earlier). This would ensure dust/lint generated during testing would be captured within the hood and filter system.

Table 2. Preliminary Fabric Testing

Fabric	Modacrylic Blend	Cotton
	Tecasafe Plus 700A	Westex Indura
Fiber Content	45% Modacrylic	100% Cotton
	35% Lyocell	FR Treated
	15% Meta-Aramid	
	5% Para-Aramid	
Weave	Twill	Twill
Color	Khaki	Navy
Weight(oz/sq yd)	7.9	7.7
Thickness (in)	0.024	0.016

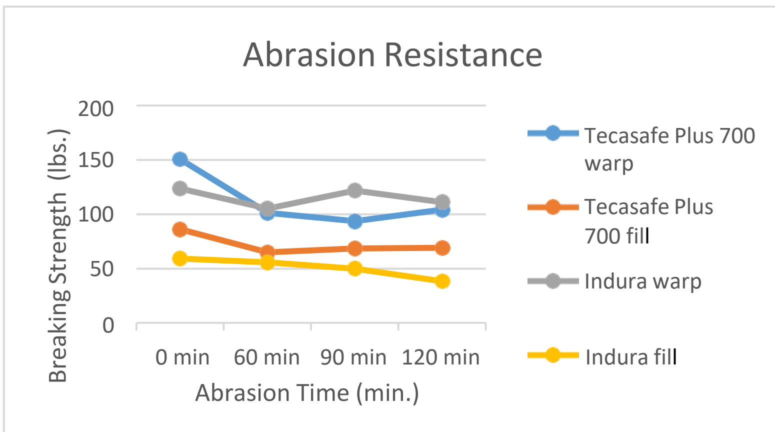


Figure 7. Preliminary Test Data

3.2 *Uniform Fabrics*

Once the preliminary tests were conducted, the necessary modifications to the test equipment were made and a ceramic deburring abrasion media referred to as "synthetic rocks" was selected. Additional testing was performed on standard uniform fabrics—ACU (50% Nylon/50% Cotton - NYCO), Flame Resistant Army Combat Uniform (FRACU) (65% FR Rayon/25% para aramid/10% Nylon- Defender M) and Army Aircrew Combat Uniform (A2CU) (92% Nomex®, 5% Kevlar®, 3% P140- Nomex® IIIA). It should be noted that the ACU fabric was cut from multiple ACU coats (end items) purchased for field testing under 18-304 Test Method for Assessment of Durability of Textile Materials and were identified as Coat, Army Combat Uniform, Unisex, 50/50 Nylon/Cotton Ripstop – NSN 8415-01-623-5553 (Large Long) and NSN 841501613552 (Large, Regular). The garments were from different contracts and manufacturers. The remaining fabrics were obtained from yardage of roll goods. Fabric details can be found in Table 3.

Table 3. Standard Uniform Fabrics

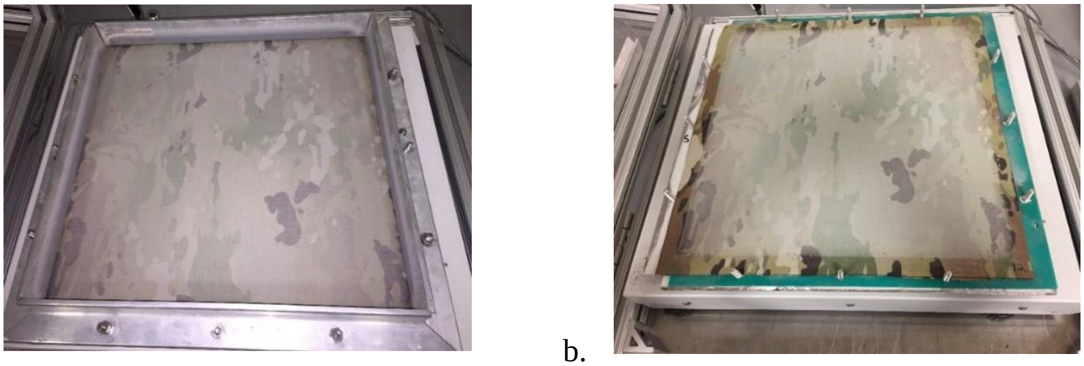
	Army Combat Uniform (ACU)	Army Aircrew Combat Uniform (A2CU)	Flame Resistant Army Combat Uniform (FRACU)
Fabric	NYCO	Nomex® IIIA	Defender M - Type III
Fiber Content	50% Cotton	92% Nomex®	65% FR Rayon
	50% Nylon	5% Kevlar®	25% Para-Aramid
		3% P140	10% Nylon
Treatments	Permethrin		XPDF
Weave	Ripstop	Plain	Ripstop
Color	OCP	OCP	OCP
Weight (oz. /sq. yd.)	6.6- 6.7	4.7 –6.0	6.2 –6.7

Fabric test panels (16″ x 16″) were cut, conditioned according to ASTM D1776/D1776M - 20 Standard Practice for Conditioning and Testing Textiles and placed on the silicone mat covering the oscillating plate. The fabric was laid flat on the plate and secured in place by screwing down the side guard. One layer of synthetic rocks was packed sufficiently onto the test fabric to allow movement. A total of 226 synthetic rocks (approximately 9 lb.) were used in testing. See Figure 8. All tests were run at 300 rpm. Testing times were altered after reviewing test data. To verify the synthetic rocks were actually making contact with the fabric surface, several rocks were painted to track their movement. The synthetic rocks successfully made their way along the surface of the fabric, indicating they were being tumbled and rolled, making contact at multiple points along the fabric surface. See Figure 8b.

a b

Figure 8. Synthetic Rocks. a. "Synthetic Rocks" (Ceramic Deburring Media) Packing on the Surface of the Oscillating Plate; b. Three Marked "Rocks" (Red, Blue, Black) Tracked to Verify Movement

After testing for the specified time, the synthetic rocks were removed from the test surface and the nuts, which held the guard (side plates) and secured the fabric onto the test apparatus, were removed so the fabric could undergo tensile testing. See Figure 9.



a. b.

Figure 9. Mounted Fabric after Testing. a. With Guard and Nuts; b. Guard and Nuts Removed

Visually, all tested fabrics had a surface layer of “dirt” or discoloration to varying degrees based on the fabric type and time tested. Lint was also visible along the guard region, particularly on the FRACU fabric samples. See Figures 10 and 11.

Figure 10. Lint on FRACU Along Guard Region (90 min)

After removing the abraded fabric, there were varying degrees of dust on the underlying silicone mat, suggesting the abrasion medium was penetrating through the fabric (between the yarns). See Figure 11 and Appendix C for photos of all fabrics.

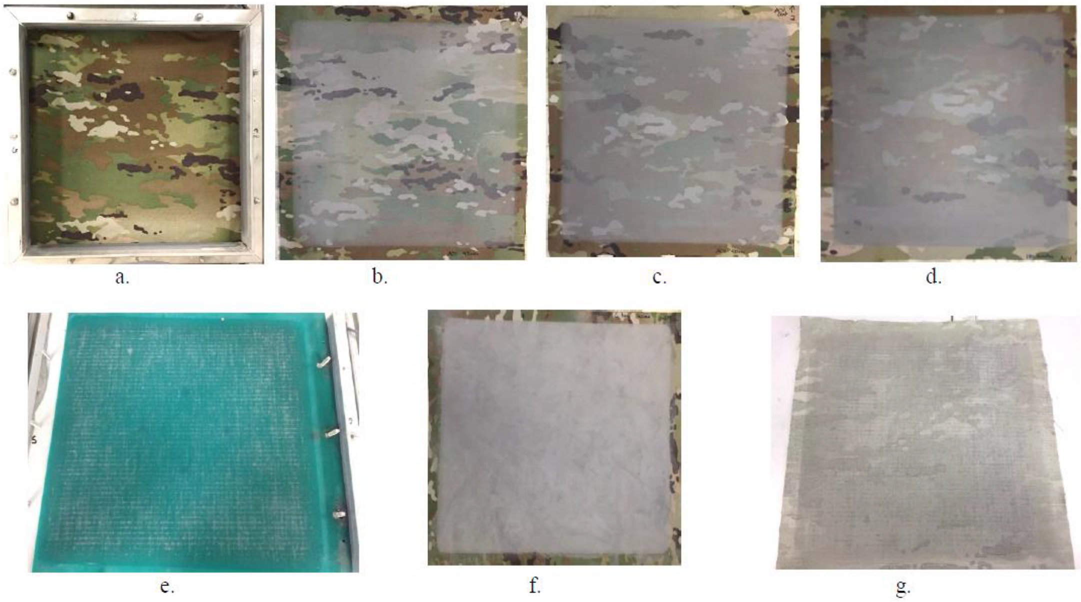


Figure 11. Abraded ACU (50/50 NYCO). a. Original; b. 45 min; c. 90 min; d.180 min; e. Silicone Mat Under ACU Fabric after 360 min, Weave Like Pattern; f. Face ACU 360 min; g. Back ACU 360 min

The silicone mat was cleaned after each test to remove any dust or debris left during testing. Once removed from the test apparatus, all samples were blown with pressurized air to remove surface dust before being cut and tested. Even after blowing, the fabrics exhibited significant discoloration on the fabric surface.

3.2.1 Test Set 1

The first set of testing was conducted using one set of "synthetic rocks" for the whole test set—45, 90, 180 min for each fabric (ACU, FRACU and A2CU) for a total of 945 min or 15.75 h of abrasion time. Testing times were selected after reviewing test data. Preliminary test data indicated the greatest change in tensile strength occurred after 60 min of testing so test set 1 was started at 45 min then doubled at each testing point beyond to determine the impact on abrasion/strength.

3.2.2 Test Set 2

A second set of tests was conducted using three sets of "synthetic rocks": one set for each fabric tested at 30, 45, 60, 90, 120 and 180 min. Each set of synthetic rocks was used for a total of 525 min, or 8.75 h of testing. This allowed a direct comparison between the fabrics, ensuring each fabric was being abraded under the same test conditions. It also provided some data on the abrasion properties of the ceramic deburring material referred to as "synthetic rocks" to help determine its effective life as an abrasion media. Testing times were selected after reviewing the data from Test Set 1. Test Set 1 indicated the greatest change in tensile strength occurred after 45 min of testing so Test Set 2 was started at 30 min then 45, 60, 90, 120 and 180, duplicating some of the previous testing times and generating some new data points between previously collected data to determine the impact on abrasion/strength.

3.2.3 Test Set 3

A third set of testing was conducted on each fabric at 360 min to determine if yarn breakage or a hole formation could be obtained—a criteria used in evaluating fabrics under some standard abrasion tests. A new set of synthetic rocks was used for each fabric tested (ACU, FRACU and A2CU). As mentioned, after removing the synthetic rocks and the guard (side plates) which secured the fabric onto the test apparatus, there was some "dust" on the surface of the underlying silicone mat. This was particularly noticeable after 360 min of testing when a weave-like pattern was left on the silicone mat. This seemed to suggest the abrasion medium was penetrating through the fabric (between the yarns). See Figure 11e and Appendix C. Lint build-up along the guard area was particularly noticeable in the FRACU fabric after 360 min of testing.

Detailed step by step instructions of the test procedure used to abrade the fabrics can be found in Appendix D.

3.3 *Results and Discussions*

3.3.1 Validating Laboratory Testing to Field Wear

Two sets of Army Combat Uniforms (ACU 50% Nylon/50% Cotton, permethrin treated) were issued to 139 Soldiers from the 10th Mountain Division, Ft. Polk, Louisiana in May 2018 under project 18-304 Test Method for Assessment of Durability of Textile Materials. Each Soldier was instructed to rotate the uniforms over the next 6 months of training; one uniform set was to be collected in November 2018 and the other in May 2019. Only 70 uniforms were returned in November and 40 uniforms were returned in May. Soldiers reported that the uniforms were worn for approximately 1 month in the field. Unfortunately, the uniforms exhibited little if any signs of wear. The little wear visible on a handful of uniforms was attributed to a specific incident such as oil or ink stains or tearing from being caught on something—not normal everyday wear. The findings from 18-304 were as follows:

- The amount of abrasion was not significant and was only present in localized areas
    - Five garment rips/frays/caught on c wire
    - One hole on knee
    - One trouser caught on fire and was discarded
    - One trouser leg ripped while wearer was getting into HUMVEE and was discarded
    - A small number of uniforms had pinholes and small tears or frosting in the back of the trousers, front legs, or backs of the coats
- The short user assessment during the collection revealed that most of the participants washed their uniform 1-3 times per week on average, those who wore the garments out in the field did so for one week every month per their training schedules, and there were almost no material/uniform failures [8].

Due to the lack of abrasion evident on the uniforms received back from the field, it was not possible to develop a rating system that would correlate laboratory testing to actual field wear in a garment. Several options were proposed to the Program Integrator for Soldier Protection & Survivability and the Susceptibility Thrust Area Manager (SusTAM) during the October 2019 program review for a path forward. The following options were presented.

Option 1: Come up with abrasion ratings that do not necessarily relate to actual field wear.
Option 2: Obtain abraded uniforms through a different method.
Option 3: Switch to the Improved Hot Weather Combat Uniform, which is a different blend of nylon and cotton (not 50/50 -6.5 oz. NYCO but 57/43 - NYCO or 62/38 - 5.5 oz. NYCO) and run future field testing at the JRTC (Joint Readiness Training Center) or JOTC (Jungle Operations Training Center) where there is better tracking of uniforms and training performed.
Option 4: Test Permethrin and/or Etofenprox resistance to abrasion. This would now be possible due to the larger surface area abraded in this new tester (15"x15"). Comparisons between permethrin treated fabrics and treated garments could also be conducted to determine the durability of permethrin and/or etofenprox to abrasion and subsequent health issues.

A decision was made to abrade standard uniform fabrics to determine proof of concept for the test method rather than redirect program funds towards additional field testing. 18-304 ended in FY19 and received no further funding.

3.3.2 Tensile (Breaking Strength) Tests

While the abraded fabrics had visual discoloration on the surface, there were no broken yarns or holes visible in the fabrics tested until the third test set run at 360 min (6 h) and then only in the FRACU and A2CU fabrics. Tensile testing was conducted on all abraded samples to determine if there had been any change in the breaking strength of the fabric. Four (4 in x 8 in) samples—two warp and two filling—were cut from each abraded test sample to conduct breaking strength tests in accordance with ASTM D4632, which is equivalent to ASTM D5034. Because of the accumulated "dust" on abraded samples, a serrated jaw was used during all tests to avoid fabric slippage. All breaking strength tests were run on Instron Model 5967, with a load capacity of 30kN using load cell serial number 021371, 1 inch x 1 inch front jaws (serrated-pneumatic), 1"x 3" back jaws (serrated-pneumatic), a 3 inch grip separation, and tested at a rate of 12 in/min. Non-abraded control samples were also cut and tested. Test results indicated the material was in fact losing breaking strength. It should be noted there was some ejection of dust from the samples during tensile testing. As mentioned, the preliminary testing indicated the greatest amount of reduction in tensile properties occurred after 60 min of abrasion, which was the minimum time cycle tested; therefore, the abrasion testing on the first set of standard uniform fabrics was started at 45 min and the second set was started at 30 min to determine the point at which the greatest change in tensile strength occurred.

The synthetic rocks were found to provide sufficient changes in all three fabrics tested (ACU, FRACU and A2CU) to affect their tensile properties with a significant change occurring in the warp yarns within the first 30 min of testing (approximately a 27, 23 and 21% reduction in warp breaking strength respectively – fill breaking strength 10, +5, 9 % respectively). Note that 30 min was the lowest abrasion time tested. See Figure 12. The warp yarns lost considerably more strength after abrasion testing than the filling yarns, which is consistent with the breaking strength data after brush pill testing ASTM D3511 conducted on the ACU fabric under project 18- 304 (decrease in breaking strength – warp approximately 57%, fill +2%). See Appendix E.

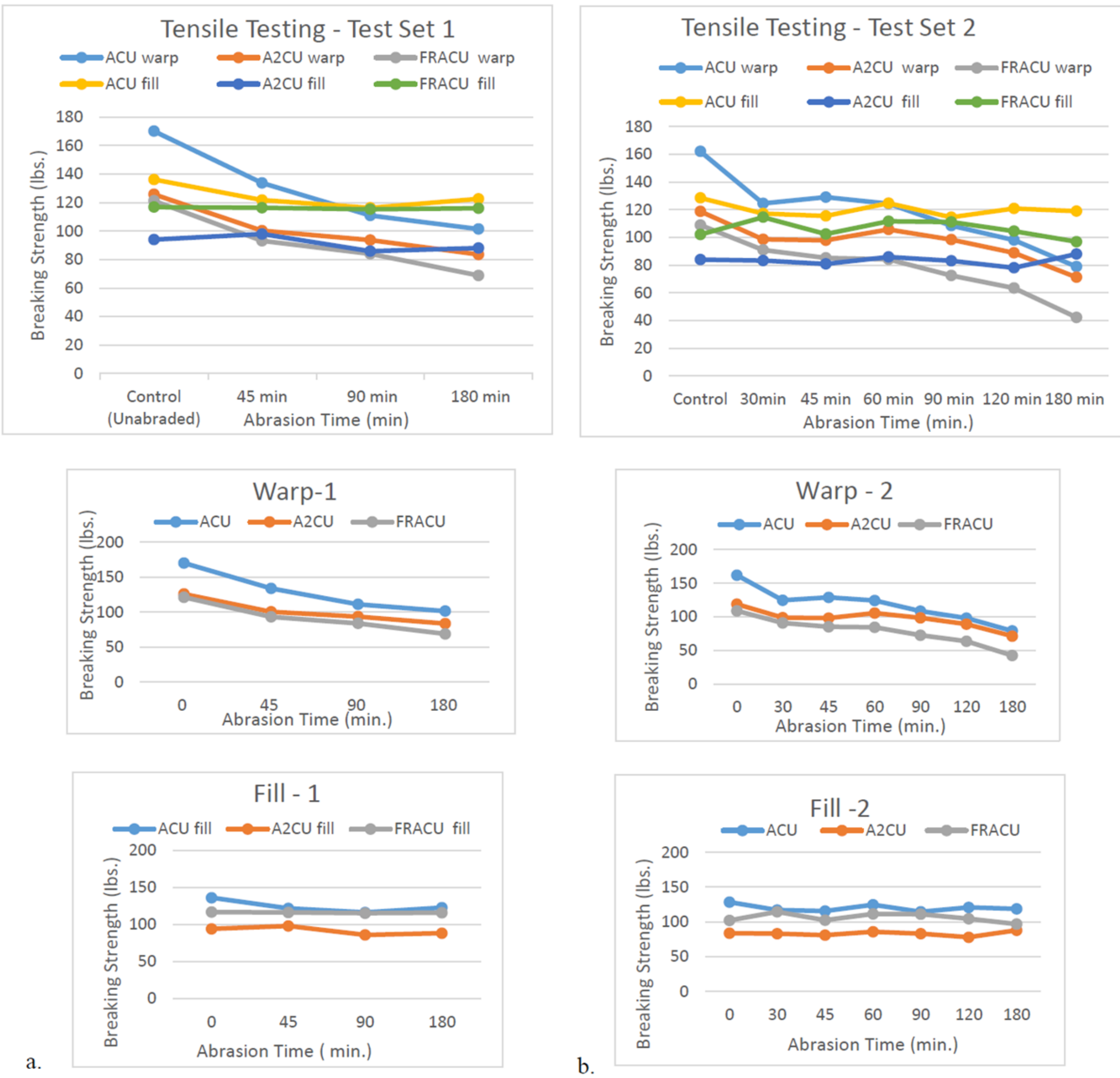
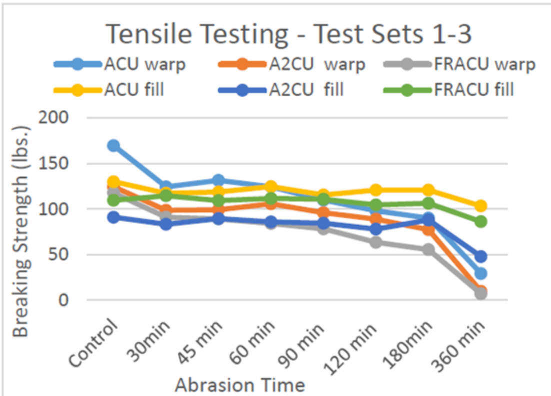


Figure 12. Tensile Test Results. a. Test Set 1; b. Test Set 2

In the third set of tests, each fabric sample was tested with a new set of synthetic rocks at 360 min (6 h). Visually, both the FRACU and A2CU exhibited small holes and areas of light penetration after this test, while the ACU did not exhibit any visibly worn areas. See Appendix C. Consistent with Test Sets 1 and 2, all three fabrics in Test Set 3 exhibited noticeably less reductions in the fill breaking strength properties (ACU 21%, FRACU 21% and A2CU 47%) while the warp breaking strength properties continued to degrade and exhibited significant reductions in tensile properties (ACU – 83%, FRACU – 94% and A2CU – 92%) in fact, close to complete tensile failures in the FRACU and A2CU were noted. See Figure 13. These data combined with the data generated from Test Sets 1 and 2 suggests that a visual evaluation of abraded material after testing, or evidence of ruptured yarns in the fabric—the criteria used in many abrasion tests—is not an adequate assessment of the abrasion resistance of the fabric or the effect of abrasion on the fabric's performance.

a. 

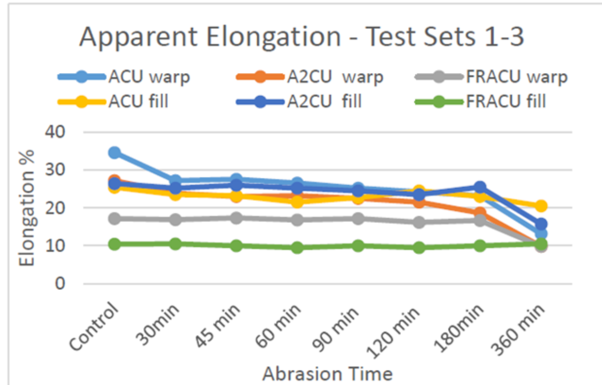
b. 

Figure 13. a. Tensile Testing Test Set 1-3; b. Apparent Elongation Test Set 1-3

3.3.3 Durability of Abrasion Media

The synthetic rocks were weighed both before and after Test Set 2 and 3 and did not exhibit any weight change. After testing, the synthetic rocks had a layer of dirt/dust on them, which was easily washed off by running them under water. While there were some visual differences in the overall appearance of the synthetic rocks after washing—slight discoloration (blackening) on portions of some synthetic rocks, mainly along the outer edges and some smoothing of the flat surfaces—there appears to be a considerable amount of rough features remaining even after 945 min or 15.75 h of testing (Test set 1). See Figure 14.


a.

b.

c.

Figure 14. Synthetic Rocks. a. Original; b. Test Set 1 With Layer of Dust/Dirt (945 min or 15.75 h of abrasion time); c. Test Set 1 Washed after Testing (945 min or 15.75 h of abrasion time)

It is known that in both Wyzenbeek and Martindale abrasion testing, the reliability of the testing process becomes more and more suspect as the abrasion cycles increase in number. For instance, the results of multiple standardized abrasion tests on the same fabric sample can vary by as much as 25,000 +/- Wyzenbeek double rubs or Martindale cycles [9]. Fabrics themselves can also exhibit variations from one area to another, or in the case of the ACU, from one garment to another, due to differences in finish applications, fabric lots etc., which can affect test results. All of these factors make it challenging to estimate the lifetime effectiveness of the abrasion media. However, based on the limited amount of breaking strength test data generated on specimens taken from the same abraded sample, there is generally good agreement as indicated by the standard deviation (in most cases below 10%). See Appendix F. The combined test data from Test Set 1 and Test Set 2 also exhibit fairly good agreement until about 180 min of testing, when the standard deviations start increasing to around 15% and differences in the warp tensile strength properties become apparent. See Figure 12 and Appendix G. After comparing data generated in all three test sets, it is estimated that the synthetic rocks can be used effectively in abrasion testing for at least 360 min (as seen in Test Set 3), possibly up to 525 min (as seen in Test Set 2). In Test Set 1, the abrasion media had been used approximately 540 min prior to the 180 min tests. Increases in the standard deviation of the ACU and FRACU fabrics when combining Test Set 1 and 2 after the 180 min test, as previously mentioned, may indicate the abrasion medium has reached the end of its lifecycle somewhere between 720 – 1080 min. In Test Set 2, the abrasion media was used for 345 min prior to the 180 min tests and 525 min after (345 +180). The lower breaking strengths on Test Set 2 after the 180 min tests clearly indicate the abrasion media is still abrading all three of the fabrics tested after 525 min of testing. More testing would need to be conducted to verify this estimation.

4 Conclusion

The oscillating motion of the test plate on the new test apparatus developed under this work effort, when combined with an abrasive media, produces a large (15″ x15″) uniformly abraded material. The versatility of the tester allows it to accommodate a wide variety of materials as well as abrasive media in order to simulate various environmental and/or operational conditions. The use of ceramic bevels or "synthetic rocks" to simulate an urban or subterranean environment were found to be an effective media in abrading standard textile fabrics. Three fabrics (ACU, FRACU and A2CU) were subjected to a limited amount of timed abrasion tests ranging from 30-360 min. All three fabrics tested exhibited significant changes in their warp tensile strength properties after 30 min of testing and continued to degrade through the 360 min tested.

Most textile specifications do not cite abrasion requirements due to their subjective nature. Additionally, there is some reluctance to quantify this property due to the lack of correlation between laboratory test data and actual field wear. Unfortunately, sufficient field wear data were not obtained under project 18-304 Test Method for Assessment of Durability of Textile Materials. Without actual field wear data, no correlation could be made between the laboratory testing on this equipment and field wear. However, this testing suggests that a visual evaluation of abraded material after testing, or using a rupture in fabric yarns or hole formation as the fabric's end point is not an adequate assessment of the abrasion resistance of the fabric or the effect of abrasion on the fabric's performance.

The "synthetic rocks" used are expected to last significantly longer than the medium used in other abrasion testing (sand paper, fabric) without breaking down and therefore would improve the reliability of the testing process. In addition, while not explored in this work effort, these synthetic rocks have the potential to be reconditioned, thereby extending their life time use in abrasion testing.

The large, uniformly abraded area obtained using this new abrasion tester provides a unique advantage over other abrasion testers. Abraded fabrics can now be cut into standard textile specimen sizes to characterize their physical properties (tensile strength, tear strength etc.) and a quantifiable assessment of their performance can be obtained. This is a capability that previously did not exist. While there is currently no program to continue the work done under this program, the equipment developed can be used in future studies to correlate laboratory abrasion testing to field wear and/or to determine the useful life or performance of fabrics, coatings and finishes after abrasion testing.

This document reports research undertaken at the U.S. Army Combat Capabilities Development Command Soldier Center, Natick, MA, and has been assigned No. Natick/TR-21/008 in a series of reports approved for publication

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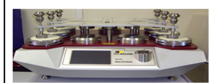
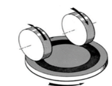
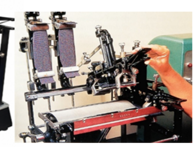
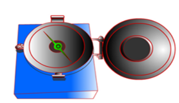
Appendix A
Standard Abrasion Test Methods [10]

Test Method	Sample Size	Standard	Description	Assessment Method	Equipment
Martindale Abrasion test	circular specimens 1.5 in. (38 mm) in diameter	ASTM D 4966	Fabric samples are mounted flat and rubbed in an enlarging elliptical T shape using worstdd wool fabric as the abradant.	The end point is reached when two yarn breaks occur or when there is an appreciable change in shade or appearance.	 
Taber Abrasion Rotary Platform, Double-Head Method	15 cm (6 in.) square, with a 6-mm (1/4-in.) diameter hole in the center	ASTM D 3884	A flat specimen is mounted to a turntable platform that rotates on a vertical axis at a fixed speed. Two abrasive wheels, applied at a specific pressure, are then lowered onto the specimen surface.	Evaluated after specified number of cycles	 
Flexing and Abrasion Method	200 mm (8 in.) long 32 mm (11/4 in.) or 38 mm (11/2 in.) Ravel each specimen to a 25 mm width	ASTM D 3885	Evaluation is made on the basis of weight loss of the specimen or grab strength loss of the specimen.	Weight loss or loss of strength	
Stoll Abrasion Test inflated diaphragm method	112 mm (43/8 in.) in diameter	ASTM D 3886	Uses a surface abrasion head (inflated diaphragm method) and Flex abrasion head.	Evaluated after specified number of cycles	
Wyzenbeek testing process Oscillatory Cylinder covered with an abradant fabric	73 mm (27/8 in.) by 245 mm (95/8 in.)	ASTM D 4157	Fabric is pulled taut in a frame and held stationary. Specimens are then lowered onto an oscillating cylinder and rubbed back and forth	The end point is reached when two yarn breaks occur or when appreciable wear is noted.	 
Abrasion Resistance Uniform Abrasion Method of Textile Fabrics	circular specimens havediameter of 61, 86 or 97 mm (2.4, 3.4 or 3.8 in.).	ASTM D 4158	The uniform abrasion testing machine is used: a specimen is mounted in a holder and abraded uniformly in all directions in the plane and about every point of the surface of the specimen.	Evaluated after specified number of cycles	
Accelerator Method	3.75-6.0 square inches	AATCC-93	Abrasion is produced throughout the specimen by rubbing of yarn against yarn, fiber against fiber, surface against surface and surface against the abradant liner.	Weight loss or loss of strength	  

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Appendix B
Parts List

The following parts were used to construct the test apparatus

DESCRIPTION	ITEM #	QUANTITY	UNIT PRICE	TOTAL PRICE
KIPP Cam Handle	20WY37	12	$5.78	$69.36
Angle Aluminum	2EYU2	2	$10.79	$21.58
Benchmark Orbital Shaker	39P097	1	$2,182.98	$2,182.98
1" Hex Bolt 1/4"-20 (25pk)	36RG16	1	$6.98	$6.98
Loctite Red permanent	5HYH9	1	$15.84	$15.84
Axial fan 115vac	2RTK6	2	$33.17	$66.34
Fan Guard	31CC66	2	$3.71	$7.42
TOTAL				**$2,370.50**

Source: Grainger
www.grainger.com

Fans

2- San Ace Fan 12v 3.5A DC Fan, 80 mm, San Ace 80 Model 9HVA0812P1G001

https://products.sanyodenki.com/en/sanace/dc/dc-fan/9HVA0812P1G001/

2- CUI Devices CFM- CFM-A238-13-10 Fan, 1.75A, 12VDC

Abrasion Medium

1” BV Wedge abrasion medium used for deburring
Purchased from Giant Finishing Inc. (https://giantfinishing.com/media/ceramic/)

Plexiglass Enclosure
Built and designed in the fabrication shop

Materials: Plexiglass
Fasonla Gas Spring- Gas Strut Model No: YQL380*150*18*8*100N

Filter – 6”ID x 9” length pleated filter, filter to 2 microns

Two power supplies – one to run each set of fans

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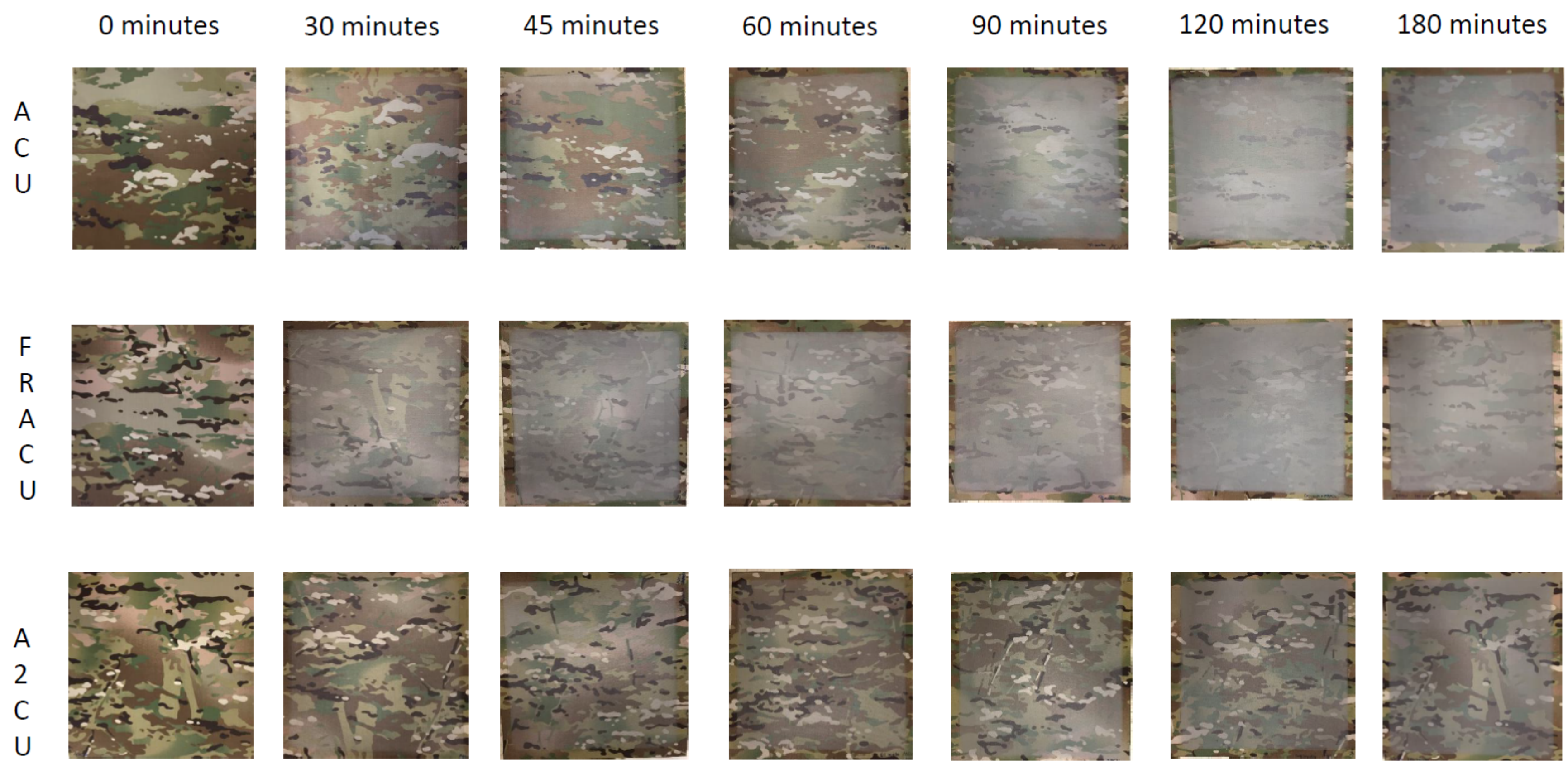
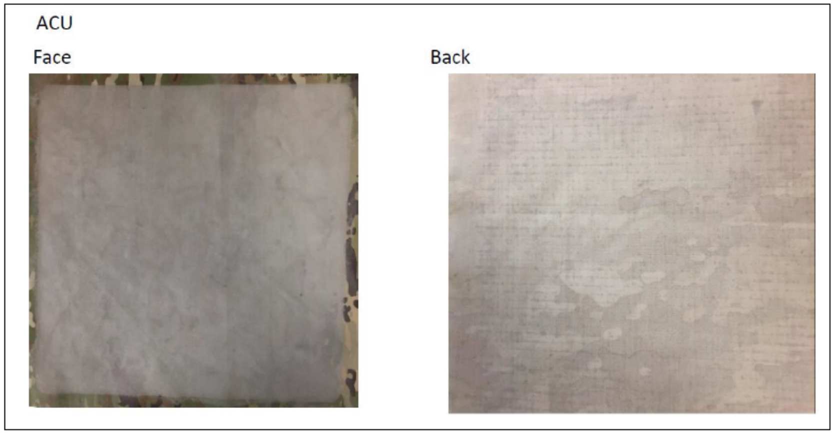
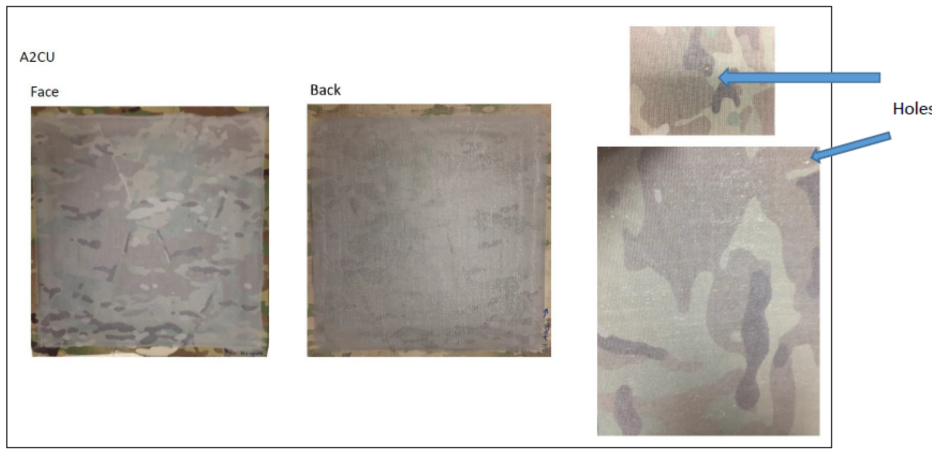
Appendix C
Photos of Abraded Fabrics



360 minutes





Appendix D
Step by Step Test Procedure

1. Open the hinged test hood carefully and secure it in an open position. Care must be taken in handling the hood, as it is heavy, could be damaged if not handled with care, and depends on the weight of the equipment to stay upright.

2. Determine the appropriate abrasion media and quantity for testing.

To determine the appropriate abrasion media, consideration needs to be given to the operational environment. For an urban, subterranean environment it was determined a 1” ceramic bevel deburring medium “synthetic rocks” could be used. This provided a more reproducible media than actual rocks, which tended to wear down and become less abrasive in testing.

To determine the appropriate amount of media to use in testing: spread the abrasive media over the plate surface and run some tests to make sure there is sufficient room for the abrasive media to move along the test surface area. The abrasive media must be able to move freely so as to roll and tumble and not just scuff back and forth.

226 (approximately 9 lb) - 1″ ceramic bevels were found to be a sufficient amount.

Weigh the abrasion test media before and after testing to ensure the same amount is used in every test and to determine if and/or the degree to which the abrasive media is breaking down in testing.

For the testing conducted, approximately 9 lb of abrasive media was used.

Remove the abrasive media from the plate.

3. Secure the test fabric.

Cut a 16” x 16” fabric. Each (16 ″x 16 ″) test specimen shall be conditioned for at least 24 h in a controlled environment to 21 ± 1 °C (70 ± 2 °F) and 65 ±2% relative humidity prior to testing in accordance with ASTM D 1776.

Place the conditioned fabric on the rubber mat covering the oscillating plate and secure in place. To secure the fabric, place the side panels of the test equipment by lining up the holes on the side panels with the screws on the test equipment. Using nuts, secure them in place—an electric drill with the proper attachment works well—ensuring the fabric is flat and tightly secured to the plate. The test fabric should be perfectly flat and free of wrinkles.

4. Once the test fabric is properly secured, the test media can be deposited onto the surface of the test sample. The media should be spread as evenly as possible across the fabric surface.

5. Set the test parameters. On the base of the test equipment there is an on/off rocker switch. Turn it “On” to illuminate the panel.

Set the time of the test and the oscillation speed of the plate. This is done be pressing the designated switches on the front panel of the test apparatus. Cycle through the time/rpm switches one at a time. Once the time/rpm test condition desired is reached, hit the “Set” button.

All the testing done to date was run at 300 rpm (maximum).

Time varied with testing. Setting the time will prompt the timer to begin counting down and the test plate will automatically stop oscillating when it reaches “0”. The test can be manually stopped at any time.

6. Next turn the hood fans on. There are two power supplies used to run the fans.

Plug in the power cord to each power supply.

Turn the power switches to “on”.

(You should hear the fans turn on, they will remain running the entire test.)

7. Press the “Start” button on the plate. The plate should start oscillating and the timer should start counting down.

8. Close the hood carefully, ensuring that the hood forms a seal and is positioned correctly over the plate.

9. When the test is complete, shut off the fans and open the hood.

10. Remove the abrasion media.

11. Remove the side panels of the test equipment which are securing the fabric by loosening the nuts and lifting off.

12. Remove the test fabric from the surface of the equipment plate. Clean the silicone mat after each test to remove any dust or debris left during testing.

13. Using pressurized air, blow the surface of the test sample to remove any loose surface debris. Further testing can be conducted on the abraded fabric samples as desired.

14. When testing is complete for the day, shut off the equipment–vibration table and power supplies. Unplug all power cords.

Appendix E
Breaking Strength After Brush Pill Test

Nomenclature: ACU-NYCO OCP Type I

Manufacturer: Multiple, 18-304 Durability Baseline

Original

Test	Test Method
Weight, oz/sq yd:	ASTM D 3776
Average	6.7
Standard Deviation	0.2
Break Strength, lbs: Warp	ASTM D 5034
Average	234.7
Standard Deviation	15.0
Break Strength, lbs: Fill	ASTM D 5034
Average	138.5
Standard Deviation	8.4

After Brush Pill Test
Tested in accordance with ASTM D3511- Tested for 15 minutes using a 240 grit sand paper - sand paper was replaced after 30 minutes of testing

Test	Test Method	Specimen ID	Results	Specimen ID	Results	Specimen ID	Results
Weight, oz/sq yd:	ASTM D 3776	C7	6.7	C26	6.7	T3	6.5
		C7	6.7	C31	6.7	T3	6.4
		C12	6.4	C50	6.4	T7	6.7
Average	6.6	C19	6.5	C50	6.4	T23	6.3
Standard Deviation	0.2	C23	7.0	T1	6.7	T32	6.8
Break Strength, lbs:	ASTM D 5034	C1	86.7	C17	138.4	C31	73.4
Warp		C7	132.8	C19	103.1	C31	89.5
		C15	90.7	C20	92.5	T3	82.8
Average	101.2	C16	154.2	C23	123.6	T4	43.5
Standard Deviation	32.4	C16	131.6	C23	124.2	T7	50.7
Break Strength, lbs:	ASTM D 5034	C3	136.2	C23	128.9	T5	137.5
Fill		C5	143.6	C31	143.7	T7	145.4
		C6	139.9	C31	156.7	T7	144.3
		C6	139.8	C32	151.8	T14	143.7
		C6	130.4	C50	124.3	T15	137.2
		C7	139.1	T3	154.0	T23	122.9
Average	141.4	C14	136.6	T3	156.4	T23	137.7
Standard Deviation	9.3	C20	145.0	T3	155.7	T24	142.3

Source [8]

Note: Breaking Strengths IAW ASTM D5034 – rubber jaws used.
Decrease in Breaking Strength - Warp approximately 57%, Fill +2% after Brush Pill Testing

****Tests conducted on ACU fabric taken from unworn uniforms purchased under program 18-304 on the Instron specified in 3.3.2 IAW (in accordance with) ASTM D5034 and D4632 show rubber jaws give higher breaking strength values (comparable to those generated in the testing above) than the same size serrated jaws (1″ x 1″ front /1″ x 3″ back jaw) as detailed below:

Rubber jaws	ASTM D5034 -236.16 lbs.	ASTM D4632- 245.40 lb.
Serrated Jaws		ASTM D4632- 169.60 lb.

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Appendix F
Breaking Strength After Abrasion - Test Set 1-3

		ACU					FRACU					A2CU				
			AVE		SDV			AVE		SDV			AVE		SDV	
				Test 1&2		Test 1&2			Test 1&2		Test 1&2			Test 1&2		Test 1&2
Control	Warp	172.68					133.26					125.44				
	Warp	167.65					119.56					120.87				
	Warp	159.96					122.67					130.33				
	Warp	164.16					109.38					126.51				
	Warp	183.57	169.60		9.09		103.85	117.74		11.52		118.92	124.41		4.56	
	Fill	135.01					121.45					96.90				
	Fill	137.43					100.28					92.55				
	Fill	124.61					126.22					93.53				
	Fill	132.35					119.35					93.01				
	Fill	117.14					109.17					85.66				
	Fill	132.88					102.11					96.37				
	Fill	128.68					103.37					88.62				
	Fill	132.41	130.06		6.51		95.02	109.62		11.38		82.27	91.11		5.16	
30 min	Warp	124.01					91.10					100.70				
Test 2	Warp	124.97	124.49		0.68		90.85	90.98		0.17		96.51	98.60		2.96	
	Fill	112.14					110.45					89.81				
Test 2	Fill	122.32	117.23		7.20		118.70	114.57		5.83		76.73	83.27		9.25	
45 min	Warp	139.38					97.22					99.91				
Test 1	Warp	128.15	133.77		7.94		89.06	93.14		5.77		100.63	100.27		0.51	
	Warp	130.48					85.77					96.59				
Test 2	Warp	127.59	129.03	131.40	2.04	5.47	84.69	85.23	89.18	0.76	5.67	99.41	98.00	99.13	1.99	1.77
	Fill	112.50					112.61					97.22				
Test 1	Fill	130.96	121.73		13.06		120.02	116.31		5.24		98.66	97.94			
	Fill	108.77					108.42					78.29				
Test2	Fill	122.36	115.57	118.65	9.61	10.02	96.37	102.40	109.35	8.52	9.89	83.55	80.92	89.43	10.07	
60 min	Warp	122.91					82.58					105.70				
Test 2	Warp	125.83	124.37		2.06		85.91	84.24		2.36		105.40	105.70		0.21	
	Fill	117.54					119.11					87.72				
Test 2	Fill	131.81	124.67		10.10		104.10	111.61		10.62		84.13	85.92		2.54	11.43
90 min	Warp	106.68					81.59					86.68				
Test 1	Warp	115.29	110.99		6.09		86.27	83.93				100.47	93.57		9.75	
	Warp	109.32					78.79					101.22				
Test 2	Warp	107.78	108.55	109.77	1.08	3.84	66.33	72.56	78.25	8.52	8.52	95.81	98.52	96.04	3.83	6.69
	Fill	111.99					121.08					83.02				
Test 1	Fill	120.59	116.29		6.08		109.49	115.28		8.20		88.69	85.86		4.01	
	Fill	116.36					99.19					92.08				
Test 2	Fill	112.77	114.57	115.43	2.54	3.93	112.92	106.05	110.67	9.71	9.07	74.15	83.11	84.48	12.68	7.84
120 min	Warp	99.35					66.24					93.88				
Test 2	Warp	96.81	98.08		1.79		60.86	63.55		3.81		83.94	88.91		7.03	
	Fill	122.66					103.41					82.50				
Test 2	Fill	119.12	120.89		2.51		105.50	104.45		1.48		73.66	78.08		6.24	
180 min	Warp	90.78					72.48					84.15				
Test 1	Warp	112.02	101.40		15.02		65.17	68.83		5.17		82.96	83.56		0.84	
	Warp	79.86					40.42					74.25				
Test 2	Warp	77.97	78.91	90.16	1.33	15.63	44.26	42.34	55.58	2.72	15.66	68.25	71.25	77.40	4.24	7.53
	Fill	120.63					122.32					87.99				
Test 1	Fill	124.62	122.63		2.82		109.55	115.94		9.03		88.08	88.03		0.06	
	Fill	123.34					96.46					91.86				
Test 2	Fill	114.55	118.95	120.79	6.21	4.47	97.36	96.91	106.42	0.64	12.17	84.22	88.04	88.04	5.40	3.12
360 min	Warp	25.84					6.30					8.31				
Test 3	Warp	32.80	29.32		4.92		7.86	7.08		1.10		10.99	9.65		1.89	
	Fill	100.75					87.94					48.50				
Test 3	Fill	105.80	103.27		3.57		84.45	86.19		2.47		47.33	47.91		0.83	

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Appendix G
Scatter Plot of Test 1&2