Investigating Abrasion Effects of Lunar Simulant Grain Sizes on Candidate Spacesuit Fabric

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Abstract— **Lunar dust is identified as one of the most significant challenges during the Apollo exploration missions due to its extremely abrasive and electrostatic characteristics. As NASA and the space industry prepare for the upcoming Artemis missions, researching and testing with lunar simulant is quintessential to understanding the effects of lunar dust on the systems and equipment that will be deployed on the lunar surface. Testing will also provide paths that lead to developing technologies and cleaning tools that could be used for dust mitigation. Additionally, it is expected that any hardware that will be exposed to the dusty environment should undergo rigorous testing to ensure it will maintain long-term performance and operate on the lunar surface. For this study, exterior spacesuit fabric was observed. Abrasion is one of the main concerns of lunar dust exposure for spacesuit fabric. Three different abrasion methods were chosen: a rotary tumbler, the Martindale method, and Accelerotor. These abrasion methods were tested on coated and uncoated spacesuit material, Orthofabric, to understand the abrasion rates of sieved lunar simulant and investigate if the addition of ceramic coating mitigated dust abrasion. To summarize, the testing results provided that larger grains are more abrasive than smaller grains, and the selected ceramic coatings did not minimize abrasion during the controlled abrasion tests. It is important to note that the selected ceramic coatings were not designed or intended to provide protection from the abrasive lunar environment. It is recommended to select additional ceramic coatings with an elevated TRL of 5 or greater for testing with Orthofabric and lunar simulant. As an additional note, contact angle measurements were not accounted for in coating selection and should be a factor when selecting adhesion resistant coatings for lunar dust.**

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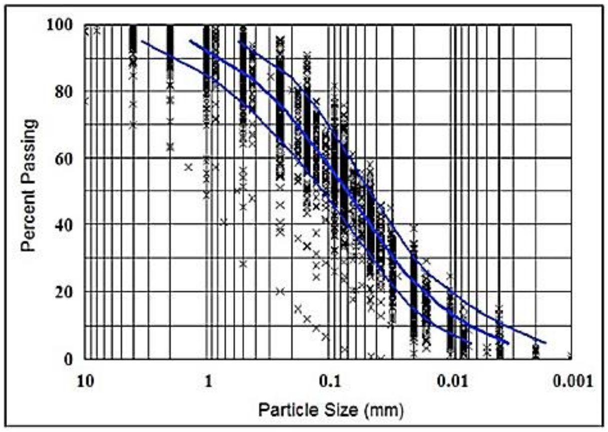
1. Introduction

Lunar Dust Introduction

Dust on the surface of the Moon has been identified as one of the most significant challenges the aerospace industry faces. While astronauts were exploring the Moon during the six Apollo missions in the late 1960s and early 1970s, lunar dust created many complications [10]. The electrostatically charged, abrasive lunar dust clogged mechanisms, scratched optical covers (lenses, instrument gauges), overheated radiators, compromised seals, irritated eyes and lungs, obscured vision during landing, and coated everything in sight with dust that was transported naturally or mechanically [10]. During Extravehicular activities (EVA), astronaut suits were exposed to the elements for approximately 21 hours while they spent about 75 hours on the surface of the Moon; including the time spent in the lunar module [10]. The Artemis missions are exploring for a much longer period than the previous Apollo missions in the 20th century; up to one week on the surface in the lander, with four or more EVAs [4].

The lunar surface has a layer of regolith composed of sharp, irregular grains that are formed from micrometeorite impacts [20]. The regolith is characterized as a silty-sand or a sandy silt [6]. The average particle size of lunar regolith is ~70-µm (0.070mm) and can be as small as 0.01-µm – see Table 1. [6], [26]. All regolith, including lunar dust, remain sharp and jagged due to the absence of fluid that would typically weather grains like those in terrestrial environments – see Figure 1 [20]. Another characteristic of lunar dust is its electrostatic properties. Solar wind plasma electrostatically charges the lunar dust, thus causing it to adhere to every surface [26]. It is theorized that electrostatic force interactions are enhanced by the cleanliness of the dust molecules and contribute to the high adhesive and cohesive behavior of the grains, but there is more research needed to investigate this [23]. Smaller grains also exhibit stronger adhesion than larger grains [23]. Surface infrared and ultraviolet radiation increases the electrostatic charge during the daytime [26]. The lack of an atmosphere and low gravity allows the dust to travel over a longer distance [16].

Table 1. Particle size (mm) of all samples collected during Apollo 11, 12, 14, 15, 16, & 17, and Luna 24 [6]. The average particle size of lunar dust is 0.070mm (70µm).



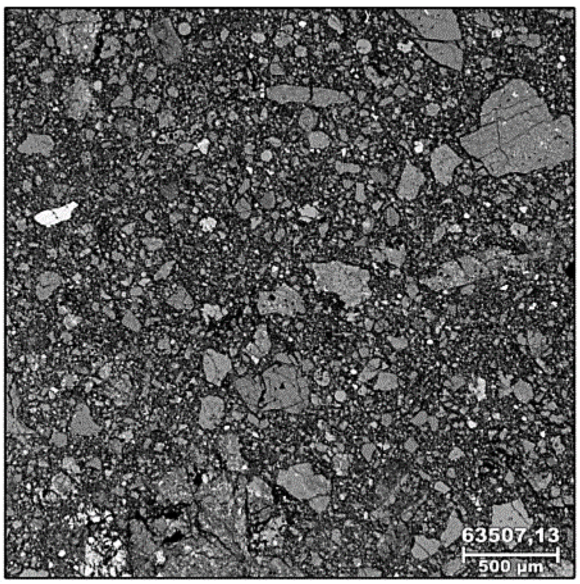


Figure 1. Apollo 16 sample #63507 represents a highland regolith breccia.

The six-landed Apollo missions had between one to three EVAs on the lunar surface - the last Apollo 17 mission only had three EVAs [10]. Each mission had known issues involving lunar dust, for instance; Apollo 12 had spacesuits that were continuing to lose pressure as they conducted each EVA due to the clogging of dust in their wrist-bearing mechanisms [10]. The first EVA created a pressure leak of 0.15 psi/min, and after the second EVA, the leak increased to 0.25 psi/min [10]. They did not have a planned third EVA, but they most likely would not have been able to perform the third EVA because the safety leak limit was 0.30 psi/min [10]. Additionally, the Apollo missions were conducted using a small spacecraft with a hatch and no airlock; known as the Lunar Module [10]. Not having an airlock decreased the ability to mitigate and separate the dust-contaminated air from different compartments within the spacecraft. As Artemis plans to conduct longer missions than Apollo, it is critical to research for new technologies and design the lunar lander for dust mitigation considerations, such as airlocks, for the safety of the astronauts [13].

Significance of Study and Objective

NASA and the space industry are working towards future sustained 30-day missions for Artemis Base Camp. An important component to the success of the Artemis lunar surface missions is to minimize the level of abrasion that the spacesuits will endure while operating on the surface of the Moon. In particular, understanding the durability of spacesuit fabric for lunar surface operations is essential for nominal operations when hardware and equipment are exposed to lunar dust. The damage to textile fibers from abrasion can lead to suit leaks and exposure to the lunar environment (O'Brien and Gaier 2009). There have been multiple projects that investigate suit abrasion with lunar simulant and Orthofabric, however no studies have been found with the addition of ceramic coatings on the Orthofabric. In this study, we evaluated the effects of abrasion on Orthofabric, which was the fabric used for the NASA reference xEMU suit and a possible candidate to be chosen for the Artemis mission. The variation of grain size and the presence/absence of ceramic coatings are evaluated.

To address how grain size and ceramic coatings affect the Orthofabric, the key goals of this study were to determine 1) how grain size influences abrasion of the fabric; and 2) if ceramic coating applied on Orthofabric reduces the abrasion produced by the lunar simulant. This study demonstrates that abrasion on Orthofabric is more likely to occur with larger grains and the ceramic coating increased the likeliness of abrasion and torn fibers. This paper describes a brief background of known Apollo lunar dust challenges on the spacesuit and EVA operations. The paper also dives into the methodology of the abrasion methods and lunar simulant selection for the tests performed.

2. Background on Lunar Dust and Suit Fabric

Apollo Mission Data

Available data regarding lunar dust is limited to anecdotal data from the lunar surface astronauts during the mid-20th century. Astronaut mission out-briefs, including video recordings and audio transcripts, provide key details regarding astronaut experiences with lunar dust. Pete Conrad noted that spacesuits were more abraded during Apollo 12's 8-hour lunar surface activity than the 100 hours they had spent in them while training on Earth [10]. Many other astronauts noted that the rate of suit joint obstruction from lunar dust would severely limit the longevity of any mission [10]. In particular, the portion of the suit near the base of the boots had been abraded through the outermost layer and exposed the insulative 2nd layer, Mylar [10].

Abrasion can lead to detrimental situations – the breaking textile fibers can create a leak in the suit and allow exposure to the lunar environment [23]. On Apollo 12, the suit material around the boots had worn a hole through the outer thermal protective layer and started on the second layer, Mylar multilayer insulation [11]. Additionally, Apollo 17 encountered a similar problem with the suit above their lunar boots, see Figure 2 [11]. During the third EVA for Apollo 17, one of the astronauts discarded their glove covers because they were too abraded from the lunar dust while drilling core samples, see Figure 3 [10]. It is common for astronauts to fall on the lunar surface, thus making it critical for the suits to endure the harsh lunar environment and dust abrasion [10].

Active attempts at dust mitigation during the Apollo missions were unsuccessful. The astronauts were given a nylon bristle brush to clean off their suits and visors. However, these brushes were only effective for coarse grains, smaller grains remained in the fabric [10]. The astronauts were not able to brush off the fine dust that had adhered to their suit from falling [10]. Dusting and banging the items on surfaces to clear the dust were no use [10]. Nylon brushes showed conflicting results when used on the radiator covers; they worked well on ground-based tests for cleaning the radiator surfaces but were very ineffective on the Moon [10]. Vibration methods worked better for dust removal, but ultimately the brushes were chosen due to saving weight [10]. Yet, these strategies proved ineffective.

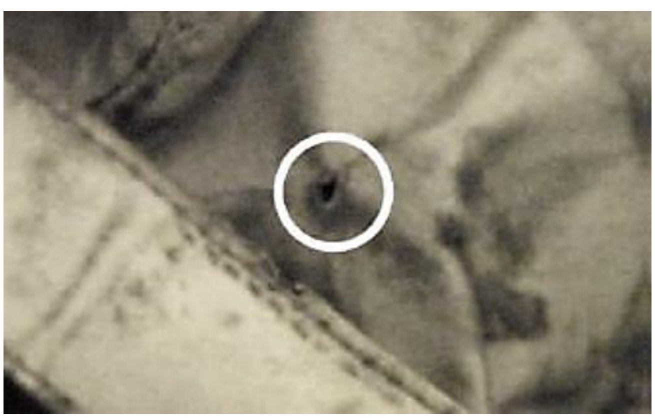


Figure 2. Lunar dust abraded a small hole worn through pressure garment assembly located above the boot for Apollo 17 Harrison Schmitt [11]. The PGA was only worn for 20.8 hours [7].

Figure 3. Gene Cernan's worn cover gloves. Note abrasion on right knuckles. [10].

Operational Challenges During Apollo

Lunar dust created a lot of operational challenges during the Apollo missions. It jammed gears and mechanisms, made tools inoperable, deemed Velcro unusable, abraded suit fabric, adhered to every surface, leaked dust out of sample bags into the command module cabin, clogged zippers, clogged the module vacuum, caused pressure leaks in suits (wrist bearing mechanism), insulated batteries (creating heating issues), scratched visors and optical surfaces, etc. [10]. Astronauts endured more suit abrasion than originally anticipated [11].

Some operational procedures had to be changed as the Apollo missions continued. For example, Neil Armstrong slipped on the ladder due to the dust being adhered to the bottom of his boots [10]. After that incident, it became standard practice to knock your boots along the side of the ladder before continuing upward into the lunar module [10]. Another operational challenge was the introduction of dust into the command module [10]. Astronauts were not very aware of the dust problem in the beginning missions; unknowingly, dust was dragged in whenever they entered and exited the hatch [10]. The later Apollo missions were able to manage this approach better due to awareness. Although dust still entered the cabin, it was at a lesser degree [10].

Optical surfaces were challenging as well. Gauge dials on the suits became unreadable from the abrasive dust after a certain period [10]. Spacesuit visors had dust accumulation that impaired their vision during EVAs [10]. During Apollo 15, James Irwin had difficulty seeing his flags due to the dust on his visor [10]. Apollo 16 had an issue with the commander’s visor not retracting – it couldn’t retract on the third EVA due to the dust [10]. Remote control surfaces were badly abraded as they attempted to brush off the dust with a glove but ended up scratching the surface instead [10].

To counter the dust problem, handheld vacuums and positive air pressure were used to clean inside of the cabin [10]. The crew also had an environmental control system with a lithium hydroxide filter that removed as much dust as it could, although it was unable to remove extremely fine dust [10].

Apollo Suit Fabric

The Apollo suit fabric is different than what is used in space today. The early Apollo mission fabric was designed to have low flammability properties, as the crew would be exposed to oxygen rich environments within the cabin [16]. The exterior fabric chosen was a woven beta fabric – Teflon-coated fiberglass 4484 [16], [7]. During the Apollo 11 mission, lunar dust was not even a consideration until the astronauts were on the surface and exploring in real-time. It did not take long to determine that beta fabric would not hold up very well due the dust abrasion on Apollo 11 suits; so, a woven Teflon ITMG (Integrated Thermal Micrometeoroid Garment) layer became the outermost layer to protect the inner beta fabric in subsequent Apollo 12+ missions [7], [12], [16]. Both Teflon T-162 and 4484 beta cloth had twill and plain weave patterns, see Figure 6 [7]. Teflon T-162 was a drawn fiber of PTFE (polytetrafluoroethylene) and single fiber weaves [16]. See Table 2 for the complete material assembly list of the ITMG fabric layers for the Apollo 12+ missions.

A previous study done by Roy Christoffersen et al has analyzed and photographed Apollo 12 and 17 spacesuit fabrics. They also observed Apollo 16's left pressure glove from Charles Duke. The Apollo 17 spacesuit is on display at the D.C. Smithsonian Museum, so only nondestructive analysis methods were allowed to observe the suit fabric with lunar dust contamination – see Figure 4 for a stereomicroscope image of Apollo 17 ITMG exterior Teflon T-164 layer with entrapped lunar dust particles [7]. Figure 5 are microscope images from Alan Bean's left knee during Apollo 12 [11]. The knees are susceptible to the most damage from lunar dust abrasion due to falling on the lunar surface.

Table 2. ITMG Fabric Layer Sequence for Apollo 12+ Missions [7].

Layer Sequence (relative to surface)	Material	1st-Level Function	2nd-Level Function	Description
1a	Teflon® cloth (T-164 8.5 oz woven Teflon® fabric)	Abrasion resistance	Flame resistance	Used for extra abrasion resistance on selected areas: knee, waist, elbow, and shoulder
1b	Teflon®-coated filament beta cloth (beta 4484)	Flame resistance	Abrasion resistance	Provided continuous outer fabric flame and abrasion resistance
2	Aluminized Kapton® film/beta marquisette* laminate	Thermal radiation protection	Thermal cross section	Provided thermal and micrometeoroid protection
3	Aluminize Mylar®	Thermal radiation protection		
4	Non-woven Dacron®	Thermal spacer layer		Provided thermal protection
Repeat 3				
Repeat 4				
Repeat 3				
Repeat 4				
Repeat 3				
Repeat 4				
Repeat 3				
Repeat 2				
5	Rubber-coated nylon (ripstop)	Inner liner	Contact layer with the TLSA	

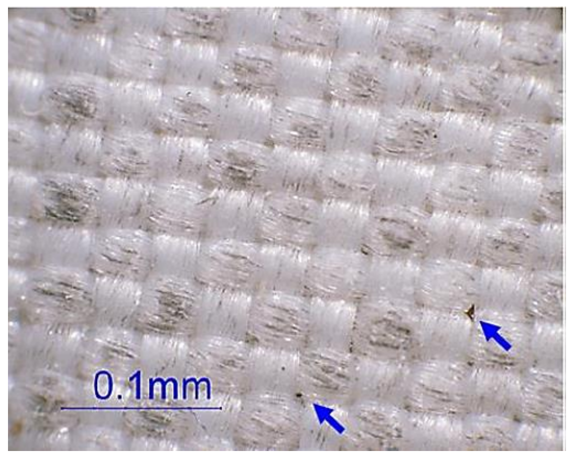


Figure 4. Stereomicroscope image of Apollo 17 ITMG outermost layer with lunar dust particles entrapped (arrows) [7].

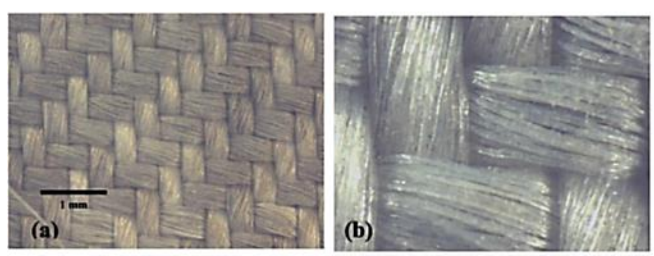


Figure 5. Apollo 12 suit swatch from Alan Bean's left knee – this is the dirtiest part of the suit due to the constant falls [11].

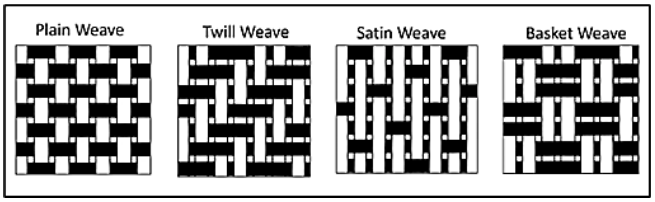


Figure 6. Pattern weaves in fabric [8].

3. MATERIALS AND METHODS

Lunar Simulant

Description—Lunar simulants are made to mimic the chemical, physical, and mineralogy composition of lunar regolith (see Table 3 below). The simulants for this study were chosen for their abrasive properties. OB-1A has 42% olivine slag glass to replicate the abrasion produced by lunar regolith [3]. LHS-1D has extra-fine smaller particles and is composed of 51.2% SiO2 (quartz), which naturally contains a higher hardness rating than most minerals; thus, being a suitable abrasion component at a lower particle size concentration for this study [9]. LHS-1D and OB-1A both represent simulants from the highland region, which is likely the landing site for Artemis. Most Apollo sites visited the mare regions, which are basaltic and younger – see Figure 4 [15]. Artemis will cross new territory deeper into the highland region on the far side of the Moon, which contains anorthosite, is highly cratered, and older [15]. The highland region also has a higher concentration of particle distribution in the smaller size range compared to the mare region due to being under micrometeorite impacts for a longer time [15].

Table 3. Bulk chemistry composition of Apollo 16 and the lunar simulants used in the study. OB-1A chemistry composition is not yet available, the Shawmere Anorthosite was used as it is a main component of the simulant [3, 5, 9].

	Bulk Chemistry Comparison			
Oxide	**Apollo 16 (64501)**	**LHS-1D**	**OB-1A**	**Shawmere Anorthosite**
	Average Soil wt%			
SiO2	45.3	51.2	-	48.4
Al2O3	27.7	26.6	-	31.6
FeO	4.2	2.7	-	-
Fe2O3	-	-	-	1.33
MgO	4.9	1.6	-	0.35
CaO	17.2	12.8	-	15.4
Na2O	0.44	2.9	-	2.47
K2O	0.1	0.5	-	0.08
TiO2	0.37	0.6	-	0.08
P2O5	-	0.1	-	<0.01
MnO	0.06	0.1	-	<0.01
Cr2O3	0.09	-	-	-
LOI	-	0.4	-	0.55
Total	100.36	99.5	0	100.26

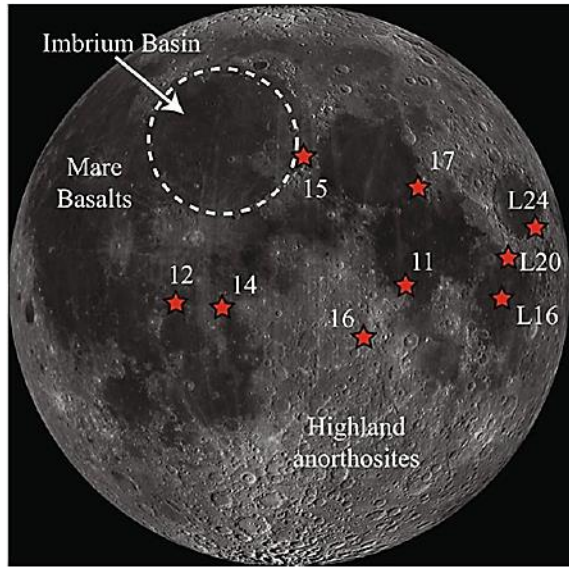


Figure 7. Apollo landing site and sample collection map [17].

OB-1A—The OB-1A simulant was developed by NORCAT from Deltion Innovations Ltd. for mechanical use [3]. The two main mineral components of this simulant are anorthosite and fayalite olivine slag glass [3]. The Shawmere Anorthosite is mined from Ontario, Canada, and is included to replicate the main mineral component of lunar highland regolith [3]. Fayalite olivine is another mineral found in the lunar highlands, so it was added to this simulant to replicate the level of abrasion found on the lunar surface [3, 15]. This simulant was originally designed for testing robotic excavation and drilling designs, but it can also be used in abrasion studies due to the similar particle distribution, mineralogy, grain shape, and density of Apollo 16 samples [3]. The overall grain shape is largely characterized as angular to sub-rounded; the glass components are more shard-like, fragmented, and angular [3]. OB-1A is considered as a high-fidelity simulant and used widely by the lunar dust community when researching physical or mechanical processes to better understand lunar regolith properties [3].

Figure 8. OB-1A consists of Anorthosite (light-colored grains) and olivine slag glass (darker grains) [5].

LHS-1D—The LHS-1D is a high-fidelity simulant which was developed from CLASS Exolith Lab for very fine dust testing needs, such as filter testing or aerosol studies [9]. 74.4% of LHS-1D is composed of an Anorthosite base and 24.7% are glass-rich basalts [9]. This simulant was chosen for this study for its small particle size distribution and representative highlands mineral composition.

Particle Size Distribution

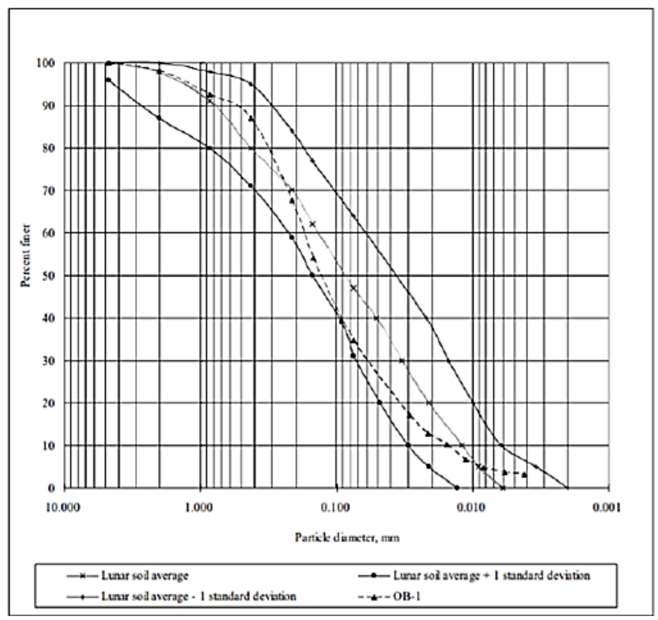
OB-1A—The particle size distribution of the OB-1A lunar simulant is distributed based on the average of the Apollo 16 lunar samples [3]. The Apollo 16 sample site location is in the highlands region, as noted in Figure 7. The mean particle size distribution of OB-1A is 72µm, which is reasonably close to the Apollo mean particle distribution of 70µm mentioned earlier in the Introduction section [6], [26]. See Table 4 on the right for the targeted particle size distribution of OB-1A compared to Apollo samples. For this abrasion study, OB-1A was sieved into two different particle size ranges – 0-106µm and 106-500µm. A particle size analysis was not tested on these samples after sieving, although it is suggested to ensure proper particle distribution. See Figure 9 below for a visual comparison of the particle sizes used, and Figure 10 and 11 for an up-close view of OB-1A simulant after sieving.

Figure 9. Left to right: LHS-1D 0.04µm-35µm, OB-1A 0µm-106µm, OB-1A 106µm-500µm, and not used but photographed for visual purposes, OB-1A 500µm+.

Figure 10. Close-up view of OB-1A, 0µm-106µm. A fresh batch of simulant was used for each tumble test.

Figure 11. Close-up view of OB-1A simulant, sieved to 106µm-500µm.

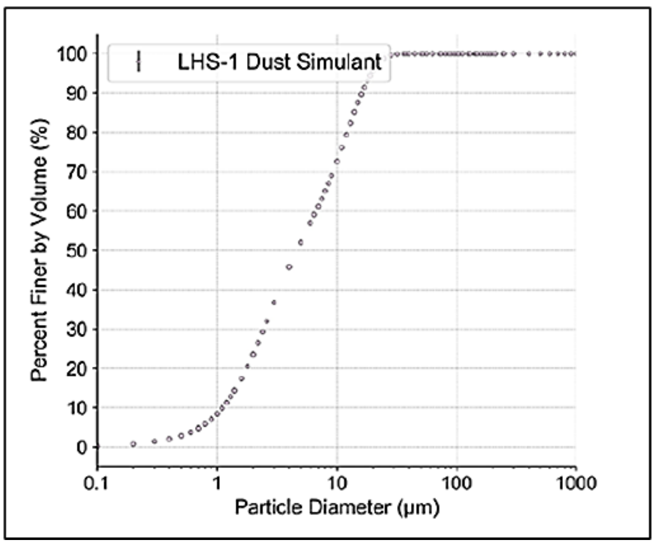
Table 4. Particle size distribution of OB-1A in mm (Credit: NASA Wiki).



LHS-1D—The particle size distribution is very small and extra fine, as this simulant is concentrated heavily on the smaller dust particles instead of regolith or soil like other lunar simulants. The mean particle size is 7µm and the particle distribution ranges from 0.04µm to 35µm [9]. This small particle size distribution allows the grains to be more cohesive and interlocking, as seen visually in Figure 12. See Table 5 for a graph of the particle size distribution for LHS-1D [9].

Figure 12. LHS-1D, 0.04µm-35µm. This simulant was not sieved, as it was already at a low enough particle size distribution for testing.

Table 5. Particle Size Distribution of LHS-1D in µm [9].



Sieving Methodology

Only the OB-1A simulant was sieved. It was sieved by an automatic sieve shaker made by Gilson Company, Inc. The sieves were also made by Gilson. The sieve shaker model used was SS-15D. The two main particle size distributions were 0-106µm and 106-500µm. There were 1200 grams total for 0µm-106µm and 1200 grams for 106µm-500µm. The simulant was stored in sealed 5-gallon containers within a 63°F climate-controlled lab of 40% relative humidity.

Figure 13. Sieving OB-1A in the Simulant Development Lab.

Candidate Suit Fabric Selected for Study

We used a publicly available NASA technical standard document as a guideline to determine our test plan for the abrasion of Orthofabric [18]. Outlined in CLASSIFICATIONS AND REQUIREMENTS FOR TESTING SYSTEMS AND HARDWARE TO BE EXPOSED TO DUST IN PLANETARY ENVIRONMENTS, there are different types of abrasion testing methods for "soft goods", such as flex abrasion or plane and flat abrasion [18]. For this study, both testing methods were used to gather more data points on the Orthofabric. When testing textiles for abrasion, it's important to pay attention to the direction of the fabric pattern (warp and wefts) as different directions can produce different results [24].

Orthofabric—The Orthofabric we use today is a double-sided fabric composed of three fibers – Gore-Tex, Nomex, and Kevlar [16]. Gore-Tex compromises 50% of the fabric, which is slit fibers of expanded PTFE (polytetrafluoroethylene) [16]. Gore-Tex is more commonly used in household items such as rain jackets and waterproof boots. Nomex encompasses an additional 45% of the fabric and Kevlar is the remaining 5% of the fabric thread [16]. Nomex is a flame-resistant fabric that is used for fire protection. Kevlar is found in motorcycle gear, as it is extremely protective and durable. The Orthofabric is a plain weave pattern (see Figure 6 on page 5 and Figure 14 below).

Figure 14. A microscope image of the clean, uncoated Orthofabric bean bag before it was tumbled.

For test setup and preparation, the Orthofabric coupon samples were prepped in four different ways. Circular 5.5” x 5.5” flat coupons were used for the Martindale abrasion test. Square 4” x 4” flat coupons were used for the Accelerotor abrasion test. Square Orthofabric bean bags were used for the tumble test. The bean bags measured 6” x 6”, were lined with a mylar insert, and then filled with 1lb of circular glass pellets. There were 9 flat 4” x 12” coupons that were taped to the side of the tumbler during the test for an additional data point with lunar simulant abrasion. The Orthofabric bean bags are not a perfect representation of a spacesuit, however, the bean bags provided a simple and repeatable testing process for spacesuit material at an attempt to thoroughly understand the abrasive properties of lunar regolith on the surface of the Moon.

Ceramic Coatings

Description—Ceramic coatings were selected for this abrasion research because of their durability in abrasive environments on Earth and generally lower surface energy. It is theorized that lower surface energy should reduce the ability for lunar dust to stick to the surface of the coating, such as a raindrop on a raincoat or a water droplet on a lily pad. Ceramic coatings have become more commercially available over the last ten-fifteen years to provide consumer paint protection on cars, boats, and aircraft. Ceramic coatings are designed to protect surfaces from UV rays, dirt, bugs, pollen, and dust. According to Kazuhisa Miyoshi, additional research is needed in ceramic coatings for the future of lunar dust mitigation because it may lead to promising performance [19]. There are several different types of base chemical components in ceramic coatings, extensive formulation work and relevant lunar environment testing will need to be conducted to characterize the proper technology for protection against lunar dust.

Chemical Guys-Hydrothread Description—Although the Safety Data Sheet (SDS) doesn’t specify the chemical composition of the coating due to trade secret, Chemical Guys Hydrothread appears to be a water-based coating due to the behavior of liquid when applied on the textile. When it was applied, the coating did not readily absorb into the textile as quickly as the Gtechniq coating – there was some surface tension, and it took a few seconds to absorb.

Gtechniq-I1 Smart Fabric Description—According to the SDS, the main ingredient of the coating formula is isopropyl alcohol. When this coating was applied, it was absorbed into the fabric immediately. Alcohol has less surface tension than water, so that explains why it was more readily absorbed into the textile. Note: Since the coating application method is the same for Chemical Guys Hydrothread and Gtechniq I1 Smart Fabric, both procedure applications will be summarized in this section.

Procedure of Coating Application—Before beginning the application of the coating, the surfaces of the samples were ensured to be clean, dry, and free of dirt/debris. The samples were placed in a well-ventilated area to circulate and remove the vapors that would disperse from the coating application. Once the ventilation area started cycling air, the samples were liberally sprayed with ceramic coating from the supplied bottle sprayer nozzle about 6-8” away from the fabric surface. Then, the samples dried in ambient laboratory conditions over the next 24 hours. After 24 hours had passed, the steps were repeated for spraying the underside of the coupons that will be susceptible to flex abrasion testing (tumbler bean bags and 4” coupons for Accelerotor test).

Abrasion Instruments

Three different abrasion methods were selected for this research because they provide varying perspectives of abrasion in controlled environments. Two of the tests, Martindale and Accelerotor, are used in the textile industry for durability and abrasion testing. These were conducted in the Advanced Materials lab at NASA Johnson Space Center. The third abrasion test is the tumbler, a rotating drum instrument that is more commonly used to tumble rocks with sand and water to round and smooth them into polished rocks. The tumbler test was conducted in the Simulant Development Lab at NASA Johnson Space Center. Microscope images were also used on all tests to provide a qualitative set of data to visually observe abrasion on the Orthofabric.

Martindale

The James Heal Martindale Model 1605 was used to perform abrasion on the uncoated and coated flat Orthofabric samples. The Martindale is a uniform abrader used worldwide for the textile testing industry as one of the methods of quality control. ASTM D4966 is the standard test method that was used with this instrument to perform the abrasion for this study. There were 15 Orthofabric coupons that were shaped into flat circles of 5.5” diameter, see Figure 16.

Description—Martindale is an abrasion method that was first developed in 1942 by Dr. J.G. Martindale at Wool Industries Research Association [14]. This method clamps a circular Orthofabric coupon on a stable sample holding tray with a backplate, then it abrades the coupon with a weight-calibrated spindle that uniformly rotates in a pattern on the surface. This abrasion method will flex each of the fibers in every direction. For this test method, a “3M BIOS 150 Grit Fine for Wood” was attached at the end of the rotating spindle to abrade the surface of the Orthofabric in a changing uniform pattern. Mass loss was taken at every 1,050 cycles on a Mettler scale and recorded until the 10,500 cycles have been completed.

Figure 15. Martindale Model 1605 used in AML at NASA JSC. Circular sample plates are abraded with rotating spindles that hold abradant grit material.

Procedure—Before testing on each of the 15 samples, the black top plate of the instrument was lifted. The sample holding trays were inspected to ensure they were free of debris and yarns. Clamp rings were removed. A 5.5” felt layer was placed first on the sample holding tray. Then a 5.5” Orthofabric coupon was placed on top of the felt layer. It is important that the next step be taken carefully to minimize accidental abrasion. When placement alignment is satisfactory, a pressing weight was gently used to secure the coupon. With pressing weight in place, the clamp ring was inserted to secure the edges of the coupon. Locking pins were used to secure clamp ring. Once clamp ring locking pins were in place, the pressing weight was gently lifted and removed. Coupon surface was inspected to ensure no wrinkles were present. If any unconformities were present, clamp ring was then removed, and sample was adjusted until placement was satisfactory. The spindle abrader was prepared next. Aside the sample holding tray is a block spanner to hold the spindle abrader nut. The abrader nut was placed in the block spanner. A 38mm 150 grit abradant was laid face down on the block spanner. The abradant was inspected to ensure there were no wrinkles present. A polyether urethane (PU) foam layer was inserted on top of the abradant and used as the backing plate. A holder insert was screwed on the spindle abrader nut to secure the foam and abradant. The edges of the abradant or foam were ensured to not stick out of the spindle abrader nut. The spindle body is then inserted to the threads of the holder insert. A loading weight of 1.312lb-f was used. The spindle was then installed on the top bearing ready for testing [25]. Martindale results for each coating was pulled from an average of 5 samples.

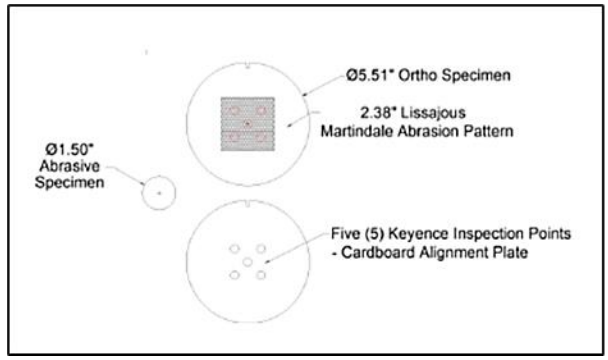


Figure 16. Sample dimensions for Martindale Abrasion Test [25].

Accelerotor

The Accelerotor test is also used in the textile industry for quality abrasion testing. The test method used was created by the American Associate of Textile Chemists and Colorists (AATCC) TM93-2005 [1]. A flat 4”x4” square coupon of uncoated and coated fabric was used for this study.

Description—The Accelerotor is a test method that is performed in a small, circular chamber which is then propelled by an impeller [1]. This forces the sample to navigate through a flexing, bending, and abrasive environment while being rotated within the chamber – a harsher version of a top-loading washing machine [1], [25].

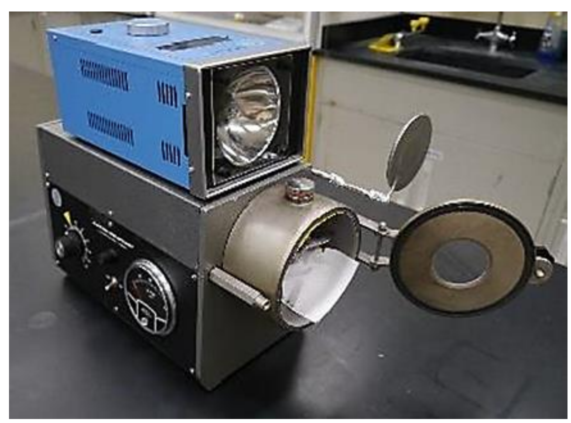


Figure 17. Atlas Accelerotor Test located in the AML at Johnson Space Center [25].

Procedure—Each Orthofabric sample was tested individually. They were placed within the accelerotor chamber with a 500-grit aluminum oxide cloth. Cloth and sample were checked to ensure no creases were present. After no creases were confirmed, the accelerotor door was closed and rpms were set to 3000. Every 6 minutes, the sample was taken out and microscope images were taken. The full run-time was 30 minutes. Accelerotor results consist of the average of 5 samples.

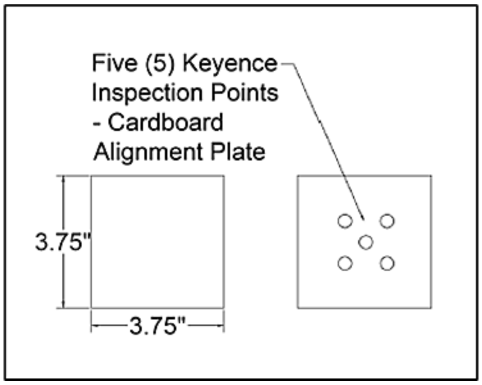


Figure 18. Sample dimensions and microscope documentation locations for Accelerotor Abrasion Test [25].

Rotary Drum Tumbler

The tumbler performed 9 runs of 1 lb. 6"x6" Orthofabric bean bag samples that tumbled at 13 rpm for 8 hours to simulate a worst-case scenario EVA of an astronaut being dragged upon the surface of the Moon.

Description—The tumble test was conducted in a rotating belt-driven drum assembly that is 16 inches in diameter and 20 inches deep [22]. The tumbler is limited to 13 RPMs. After 8 hours, 13 RPM averages around 6,240 rotations. The tumble test ran for an uninterrupted 8-hour period to simulate a worst-case EVA of an astronaut being dragged on the surface of the Moon. Additional time was spent cleaning the interior of the tumbler after each test period. Each tumbler run composed of an Orthofabric bean bag, a flat Orthofabric coupon taped to the inner wall, and 400g of lunar simulant.

Figure 19. Rotary drum tumbler in the Simulant Development Lab at NASA Johnson Space Center. It ran for 8-hour periods at 13 RPM with Orthofabric bean bags and lunar simulant to simulate a worst-case scenario of an EVA.

Test Procedure—Before operating each test, the tumbler was inspected for residual particles from previous tests with an air pressure nozzle. After the air test ensured no particles remained inside, a 4" x 12" Orthofabric coupon was securely taped to the inner wall of the drum with 2" white Gaffer tape and a 3"x5" area of Orthofabric exposed. Gaffer tape was chosen for durability and because it didn't leave behind any glue residue when removed. The tape was firmly pressed after it was initially applied to remove any air bubbles and ensure maximum adhesion.

Once the sample was firmly taped to the inner wall, a portion of tape was labeled with a sharpie indicating the coating brand name and simulant selected for the run. After labeling, an Orthofabric bean bag was placed directly in front of (not on top of) the 3"x5" exposed Orthofabric. Photographs were taken before lunar simulant was added (ensured label was clear in the photos). After the photograph documentation, the lunar simulant was carefully deposited directly on top of the 3"x5" exposed area (see Figure 20 and 21 below). Another photograph was taken to document the simulant deposit.

Figure 20. Tumbler set-up before lunar simulant and bean bag were added. Coupon was secured by 2” white Gaffer tape and 3” x 5” inches of Orthofabric were exposed.

Figure 21. Tumbler test set-up after bean bag and 400g of lunar simulant were added.

Once the fresh batch of simulant was placed inside the tumbler and photos were taken, the drum lid was installed, and the tumbler was turned on. Samples were tumbled at 13 RPMs for 8 hours. After the 8-hour tumble cycle, photographs were taken to document the layout of the drum, bean bag, and flat coupons. After gently liberating any loose dust from the bean bag (via shaking), the bean bag and remaining simulant were removed. Any dust that may have passed through the taped Orthofabric coupon was photographed and collected in a separate container. Lunar dust simulant was thoroughly removed from the tumbler prior to each tumble test with a wet cloth and air pressure.

Abrasion Analysis

Microscope—A Keyence VHX-7000 microscope was used to capture the abrasion images in the Simulant Development Lab and Advanced Materials Lab. For the Martindale test, photos were taken every 1,050 cycles at 50x magnification. Accelerotor images were taken every 18,000 cycles at 50x magnification. For the tumbler test, microscope photos were taken prior and after the 8-hour abrasion at 50x through 200x magnification. The microscope images will provide qualitative analysis of pre- and post-abrasion photos of the Orthofabric during the three different abrasion methods.

Description—Most of the images captured from the tumbler test were composites of several layered photos within one image to provide a focused image all the warps and wefts of the fabric. Since the Orthofabric has several thread layers, half of the image is blurry during normal microscope images at higher magnification due to the height difference of the threads if the composite method wasn’t used.

Procedure—A paper template with 5 small, labeled window locations was used to capture the same reference image on all the bean bags from the tumble test to ensure each impact point was captured in the same location – see Figure 22. Table 8 microscope images are from the upper right corner of the bean bag. This area appeared to receive the most abrasion across all the bean bags from the tumble test.

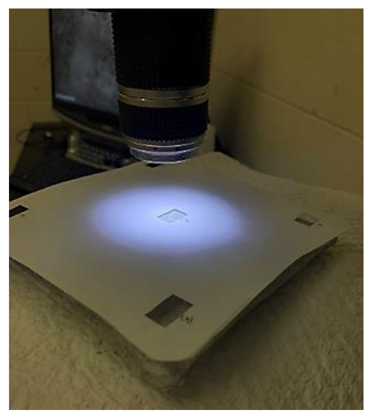


Figure 22. Window template to capture the middle and outer corners of the bean bag. This was used on all the bean bags to reference the exact same area during the point of impact from tumbling.

Puncture Test

Description—The puncture test was used to provide quantitative data of the Orthofabric. It reports the maximum breaking strength of the material after it endured the abrasion testing. Baseline results were captured on samples that did not endure any abrasion. It is assumed that the more strength it takes to break the sample, the less abrasion the sample endured during the test. This is a destructive test, so it is typically done in the final steps of the analysis [27].

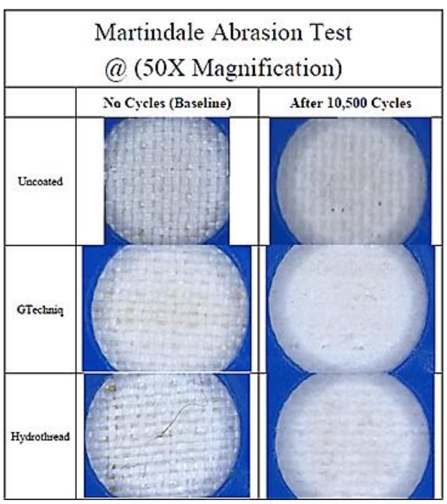
Procedure—ASTM D571, Section 22 was the method chosen for this procedure [25]. The Orthofabric is held taut with clamps that allows room for stretching in the center. A measured force is applied in the center with a 0.315" diameter probe that had a flat end with a 45° chamfer edge [25]. Once the sample is punctured, the lbf (pound-force) measurement is captured to determine the puncture strength of the Orthofabric [25], [27].

4. RESULTS

Martindale

Martindale abrasion microscope before and after images are seen in Table 6 below to visualize the level of abrasion. Images were taken at 50x magnification. The left column shows the Orthofabric before it was abraded, and the right column is after 10,500 cycles of abrasion with the 150 grit abradant. Each row is separated by coating type. After Martindale testing, the samples were punctured to quantify the abrasion results. Puncture results are captured in Table 11.

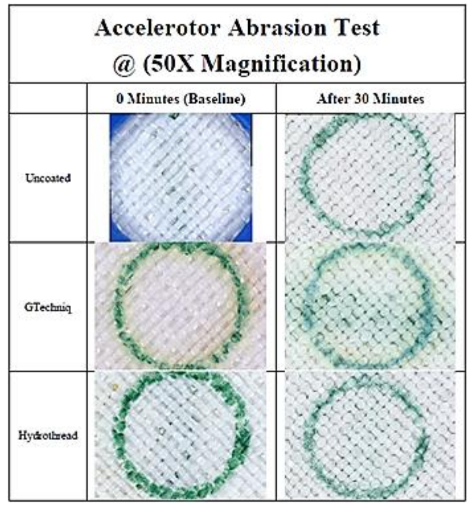
Table 6. Martindale Abrasion Test (before and after) microscope results for uncoated, GTechniq, and Hydrothread samples from the AML.



Accelerotor

Accelerotor abrasion microscope before and after images are seen in Table 7 below to visualize the level of abrasion. Images were taken at 50x magnification. The left column shows the Orthofabric before it was abraded, and the right column is after 90,000 cycles of abrasion with the 500-grit aluminum oxide cloth for 30 minutes. Each row is separated by coating type. Originally, a blue template was used to document microscope imagery, but the samples shrank after abrasion – so a green sharpie was used to track the imagery area. After the accelerotor testing, the samples were punctured to quantify the abrasion results. These results are graphed in Table 12.

Table 7. Accelerotor Abrasion Test microscope results at 50x magnification before and after 90,000 cycles.



Tumbler

For reference of the Orthofabric prior to abrasion in the rotary tumbler, Table 9 captures a pre-abrasion uncoated Orthofabric. Table 8 documents the post-abrasion results of the Orthofabric bean bags after tumbling for 8 hours. Starting in the leftmost column, the grain size increases from left to right: LHS-1D, OB-1A 0-106µm, and OB-1A 106-500µm. From top to bottom, the samples are uncoated, Chemical Guys Hydrothread, and GTechniq. Samples were not cleaned after tumbling, just gently shaken to remove any loose simulant. This was to avoid any accidental abrasion from the user.

Table 8. Microscope images of Orthofabric after the 8-hour tumble test. Note: Samples were not cleaned after tumbling, just gently shaken as to not further abrade the textile surface before data collection.

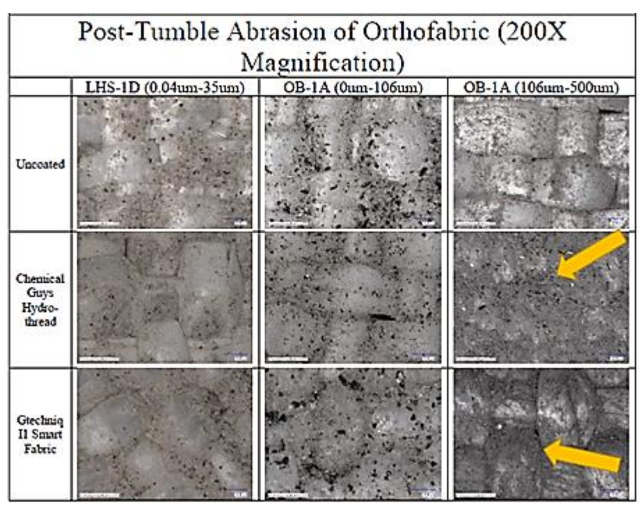
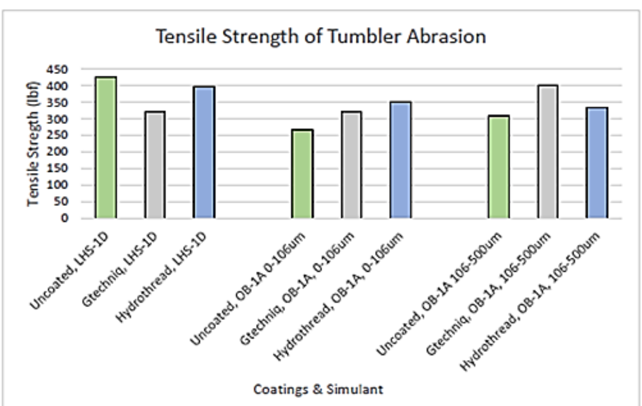


Table 9. Reference photo for Orthofabric prior to tumbling. No broken fibers, glossy appearance, and uninterrupted weaving pattern.

Table 10 captures tensile strength of the taped Orthofabric samples in the rotary drum tumbler. This test was only repeated once per sample, no duplicate samples were used. Best practices require at least 5 samples due to variability in the results. The tensile test was used to provide quantitative tumbler abrasion results from the lunar simulant. On the x-axis, each simulant is grouped in threes, from left to right: LHS-1D, OB-1A 0-106µm, and OB-1A 106-500µm. Uncoated sample results are green, Gtechniq is gray, and Hydrothread is blue. For the y-axis, tensile strength is measured in lbf (pound-force).

Table 10. Tensile Strength of Orthofabric taped on the inner wall of the rotary drum. Only a 3"x5" section of Orthofabric was exposed and abraded by the simulant.



Puncture Test

A puncture test was performed on Orthofabric samples before and after the Martindale and Accelerotor abrasion tests. This was to provide quantitative analysis of the abrasion. Table 11 is pre-and post-Martindale abrasion with standard error bars and puncture results; and Table 12 captures pre-and post-Accelerotor abrasion results with standard error bars and puncture results. On the x-axis from left to right, the Orthofabric samples are grouped synchronously: uncoated, Gtechniq, and Hydrothread. The y-axis is the amount of lbf (pound-force) it took for the sample to be punctured before and after abrasion.

Table 11. Puncture test results before and after samples were abraded with the Martindale method.

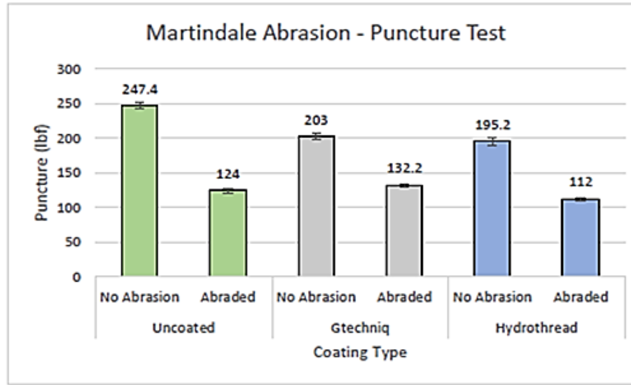
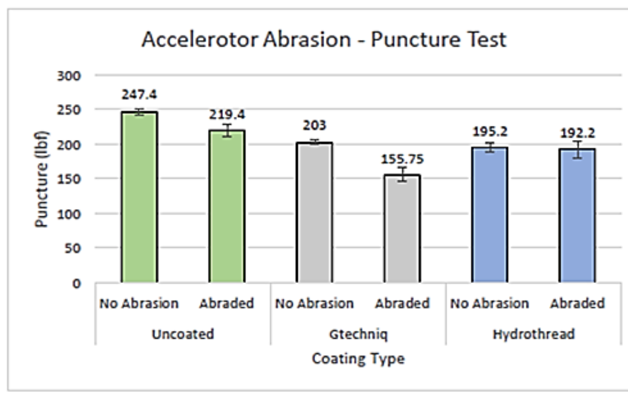


Table 12. Puncture test results of Orthofabric before and after Accelerotor Abrasion method.



5. Discussion

Discussion—Addressing the first key question, "how does grain size influence abrasion of the fabric", the rightmost column in Table 8 visually appears to have more broken fibers than the other samples of varying grain sizes – signifying abrasion of lunar dust is more likely to occur in larger grains than smaller grains. Upon visual inspection of the most abradant simulant used in the study, OB-1A 106µm-500µm, it physically appears darker than the others – this is due to a higher concentration of olivine slag glass in this particle size range. As the olivine slag glass is the angular, shard-like abradant component in this simulant, it contributes to the theory that OB-1A 106µm -500µm is the most abrasive. Unfortunately, the tensile strength data of the taped samples in Table 10 does not correlate with the bean bag sample visual analysis. There is not enough stochastic behavior from the tensile dataset to lead to a conclusive result of which simulant was more abrasive along the tumbler wall.

To address the second question, "does the application of ceramic coating reduce abrasion produced by lunar simulant", the ceramic coatings used in this study provided results that were opposite than expected. In rows 2 and 3 of Table 8, the tested ceramic coatings both appear to be more abraded than the uncoated sample in row 1; thus, revealing that the chosen ceramic coatings did not mitigate abrasion and provided opposite anticipated results of protecting the suit fabric. Due to the higher surface adhesion of the coatings, there are more torn fibers found in the coated samples than the uncoated samples. The puncture tests in Table 11 and 12 supports this conclusion due to the two coated samples taking less lbf (pound-force) to puncture the samples, signifying that they are weaker. There was also more simulant adhered to the ceramic coated bean bags after tumbling, allowing grains to stay attached, adhered, and abrade fibers. On close examination of the images in Table 8, one can see more of the grains intwined within the fibers of the fabric for the coated samples than the uncoated ones, especially the Gtechniq and OB-1A 106μm-500μm.

The Chemical Guys Hydrothread with OB-1A 106μm-500μm simulant appears to be the main sample with the most level of abrasion damage – it lost its original shape and has the most torn fibers under the microscope. This correlates to the Martindale puncture test results in Table 11 as well; the Hydrothread after abrasion was the sample to take the least amount of pound-force before being punctured.

Lessons Learned—One of the issues that the rotary drum tumbler test encountered is the lunar simulant clumped up on the Orthofabric bean bag and adhered to it like a paste during the tumble test. This could be related to a coating curing issue where the coating didn't fully cure in ambient conditions (even though it was directed that it just needed 24 hours to air dry). UV curing or setting in an oven could potentially address this problem. It's also possible that the tumble test was performed in a room with too high of relative humidity and clumped in the tumbler due to the humidity content. If one wishes to replicate this study, it is recommended to further test this research in a room with 10% or less relative humidity and bake-out the lunar simulant to remove any residual moisture.

Forward Work—No other ceramic coating abrasion Orthofabric studies are known to the authors, so results were not compared to previous work. However, future work is recommended to continue researching other ceramic coating technologies for Orthofabric and additional substrates for mitigation of lunar dust. When selecting ceramic coatings for the next study, it is suggested to search for coatings with high contact angle measurements. The high contact angle properties will reduce contact with the surface area and minimize the dust adhesion found in the coated sample results. This should correlate to reducing lunar dust abrasion, but more research is needed to verify this statement. This study was not continued, but additional research is recommended to minimize gaps in lunar dust mitigation.

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REFERENCES

[1] AATCC (2019). "TM093-TM93-TM 93 Abrasion Resistance of Fabrics: Accelerotor Method." from https://members.aatcc.org/store/tm93/508.

[2] ARES. "Overview - OB-1/Chenobi." Retrieved 4/18/2022, 2022, from https://ares.jsc.nasa.gov/projects/simulants/ob-1.html.

[3] Battler, M. M. (2008). Development of an anorthositic lunar regolith simulant: OB-1.

[4] Bridenstine, J. (2020). NASA's Lunar Exploration Program Overview - Artemis Plan.

[5] Cannon, K. (2022). "OB-1/CHENOBI Olivine Bytownite." Planetary Simulant Database. Retrieved 4/21/2022, from https://simulantdb.com/simulants/ob1.php.

[6] Carrier, D. (2005). "The four things you need to know about the geotechnical properties of lunar soil." Lunar Geotechnical Institute: 2-9.

[7] Christoffersen, R. and J. F. Lindsay (2009). Lunar dust effects on spacesuit systems: insights from the apollo spacesuits, Johnson Space Center.

[8] Database, P. P. (2022). "Encyclopedia of Fiber & Textile Technology." from http://polymerdatabase.com/Fibers/Fiberpedia%20W.html.

[9] Exolith (2022). "LHS-1D Lunar Highland Dust Simulant." Exolith Lab. from https://exolithsimulants.com/products/lhs-1d-lunar-highland-dust-simulant.

[10] Gaier, J. R. (2005). The Effects of Lunar Dust on EVA Systems During the Apollo Missions.

[11] Gaier, J. R., et al. (2009). Abrasion of candidate spacesuit fabrics by simulated lunar dust. 39th International Conference on Environmental Systems (ICES).

[12] Gondhalekar, M., et al. (2020). "Mitigation and prevention of lunar dust on NASA Artemis xEMU spacesuits."

[13] Group, I. A. W. (2016). Dust Mitigation Gap Assessment Report.

[14] Heal, J. (2017). Operator's Guide - Martindale Abrasion and Pilling Testers, James H. Heal & Co. Ltd.

[15] Heiken, G. H., et al. (1991). Lunar Sourcebook, a user's guide to the Moon.

[16] Hennessy, M. J. (1992). Electron Microscopy Abrasion Analysis of Candidate Fabrics for Planetary Space Suit Protective Overgarment Application.

[17] J.F. Pernet-Fisher, K. H. J., D.J. P. Martin, K.L. Donaldson Hanna (2017). "Assessing the shock state of the lunar highlands: implications for the petrogenesis and chronology of crustal anorthosites." Scientific Reports 7.

[18] John, K. K. and C. E. Rogers (2021). Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments.

[19] Kazuhisa, M. (2007). "Solid Lubricants and Coatings for Extreme Environments: State-of-the-Art Survey." NASA 16: 16.

[20] Kobrick, R. L., et al. (2011). "Defining an abrasion index for lunar surface systems as a function of dust interaction modes and variable concentration zones." Planetary and Space Science 59(14): 1749-1757.

[21] Kring, J. D. S. a. D. A. (2019). "Lunar South Pole Atlas." from https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/.

[22] Mitchell, K. (2010). Abrasion Testing of Candidate Outer-layer Fabrics for Lunar Extravehicular Activity Space Suits. 40th International Conference on Environmental Systems.

[23] O'Brien, B. J. and J. R. Gaier (2009). "Indicative Basic Issues about Lunar Dust in the Lunar Environment." Lunar Exploration Analysis Group (LEAG).

[24] Özdil, N., et al. (2012). "Analysis of abrasion characteristics in textiles." Abrasion resistance of materials: 119-146

[25] Settles, J. (2022). AML-22-33 Ortho Coating Abrasion Test. Crew and Thermal Systems Division. Advanced Materials Test Laboratory.

[26] Stubbs, T. J., et al. (2007). "Impact of dust on lunar exploration." URL: https://www.nasa.gov/centers/johnson/pdf/486014main_StubbsImpactOnExploration.4075.pdf

[27] Yalcin, D. (2019). "Puncture Testing Essentials." Retrieved 4/30/22, 2022, from https://www.admet.com/puncture-testing-essentials/.

BIOGRAPHY

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