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SPECIAL REPORT 94-16

Abrasive Properties of Test and Training Site Soils

Relative Hardness of Fine Particle Fraction

Austin W. Hogan

June 1994

Abstract

The experiment reported here shows that fine soil particles contribute to abrasion, wear and ultimate failure of parachute materials in a manner somewhat analogous to "three-body abrasion" in metals. The "hardness" of the particles collected at several test, training and maneuver areas is examined and scaled to known natural materials and commercial abrasives. The geometric diameters of the soil grains that enter and imbed in the fibers are a primary factor for understanding the abrasion mechanism. In the case of cordage abrasion, the fraction of soil grains less than 0.2 mm was dominant within the strands and among the fibers. The particles were applied to designated surface grids on relatively large (3×3 to 7×7 cm) Mohs hardness specimens, glass photographic plates and steel cutting tools. All of the fine particles abraded glass photographic plates, with the exception of a soft, nonmagnetic, black fraction found in Camp Blanding fines. None of the materials scratched corundum, although it was possible to make a few scratches in Topaz with almost all specimens. The general upper limit of hardness was similar to that of quartz, which showed some detectable abrasion by five specimens. Fines from the Riyadh, Saudi Arabia, area easily scratched quartz, and this material is the hardest measured to date.

For conversion of SI metric units to U.S./British customary units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-89a, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

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Special Report 94-16

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Abrasive Properties of Test and Training Site Soils

Relative Hardness of Fine Particle Fraction

Austin W. Hogan

June 1994

Prepared for
U.S. ARMY NATICK RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

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PREFACE

This report was prepared by Dr. Austin W. Hogan, Research Physical Scientist, Geochemical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Parachute Engineering Branch, Airdrop Systems Division, Aero-Mechanical Engineering Directorate, U.S. Army Natick Research, Development and Engineering Center.

Technical review was provided by E. Cortez and Dr. G.S. Brar, both of CRREL.

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EXECUTIVE SUMMARY

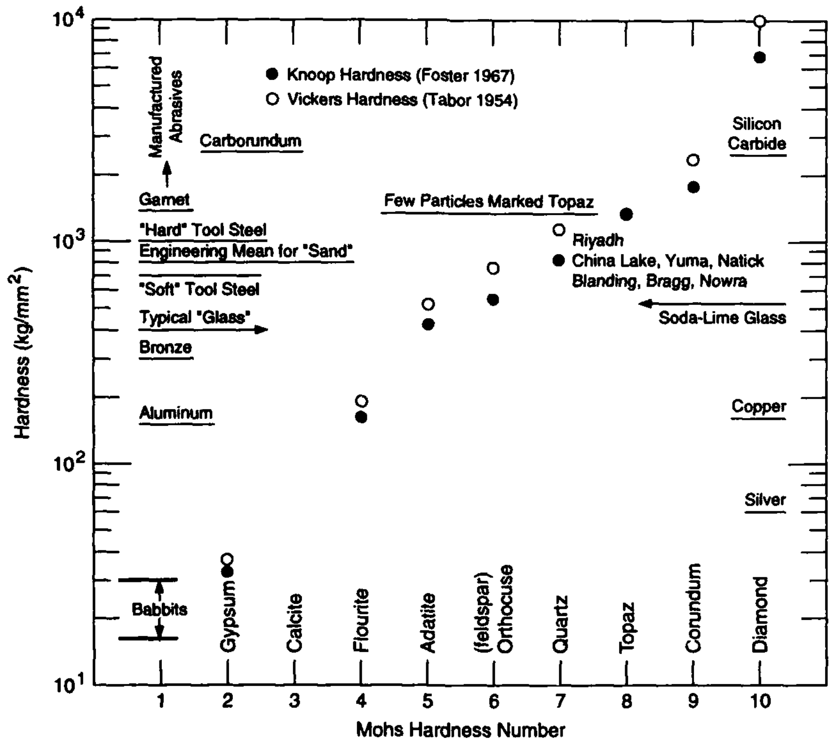
Soil specimens from seven paratroop training drop zones, two proving ground cargo chute test areas, and the Natick RDEC drop test pit were analyzed to examine the influence of physical properties of soil on abrasion of parachute materials. Additional analyses were performed on soil retained within the braid and core of parachute cord test specimens, and test plates exposed near rigger's tables at troop training sites.

The size distribution and clay mineralogy of the specimens were quite different. Surface material from the Saudi and Israeli deserts approached spherical symmetry, while surface materials from test sites at China Lake and Yuma Proving Ground are quite angular. There was a great difference in the mass fraction of fines among the several samples, but all contained material in the range below sieve size. The fraction below sieve size consisted of angular, aspheric particles in all cases, including those specimens that were dominated by nearly spherical particles in the larger size classes.

Several parachute lines that had previously been strained and exposed to local soil material in the Natick drop test pit were examined for soil residue. The fine fraction of soil penetrated coreless braid, and the smallest particles present were retained within the strands of the braid. Fine particles were found between core strands subjected to a single test drop, although the surface of the exterior braid looked clean.

Individual soil particles caused abrasive damage to delrin test plates in a simple sliding friction test. A more specific experiment was considered necessary to examine the abrasion of textile strands by the smallest size fraction of the soil material. I proposed that a microscopic method of measuring soil particle hardness by relating size-classified soil particles to Mohs hardness standards could be used to provide an index of soil abrasion.

This experiment shows that fine soil particles contribute to abrasion, wear and ultimate failure in textile materials in a manner somewhat analogous to "three-body abrasion" in metals. The particles of diameter comparable to the strands of yarn enter the interior of the yarn during flexing and stress. Particles harder than the yarn fiber imbed in some fibers, and then abrade another "third body" fiber as stress and flexing continue. I



Comparison of Vickers, Knoop and Mohs hardness scales.

have examined the "hardness" of the particles collected at several test, training and maneuver areas, and attempted to scale the hardness of these fine particles relative to known natural materials and commercial abrasives.

It is important to note that the geometric diameters of the soil grains that enter and imbed in the fibers are a primary factor for understanding the abrasion mechanism. Classic wear and friction experiments in conventional machinery show diminishing wear as the diameters of abrasive particles drop to less than 0.2 mm. In the case of cordage abrasion, the fraction of soil grains less than 0.2 mm was dominant within the strands and among the fibers. This made it necessary to extract the fine fraction of the soil particle population for these experiments. The fine fraction was further classified into $0.105 < d < 0.125$ mm, $0.044 < d < 0.053$ mm, and $d < 0.044$ mm classes to provide uniform grit.

The grits were applied to designated surface grids on relatively large (3 × 3 to 7 × 7 cm) Mohs hardness specimens, glass photographic plates and steel cutting tools. The grits were imbedded in the flat face cut at 30° to the axis of hardwood dowels and rubbed over the surface, simulating three-body abrasion. In some cases, abrasion was apparent through sound and feel; in other cases, microscopic examination was necessary to determine if the particles had deformed the hard surface.

All of the fine particles abraded glass photographic plates, with the exception of a soft, nonmagnetic, black fraction found in Camp Blanding fines. None of the materials scratched corundum, although it was possible to make a few scratches in Topaz with almost all specimens. A few particles of greater hardness are apparently naturally occurring contaminants in many soils. The general upper limit of hardness was similar to that of quartz, which showed some detectable abrasion by five specimens. Fines from the Riyadh, Saudi Arabia, area easily scratched quartz, and this material is the hardest measured to date. Fines from China Lake, Natick and Yuma quickly produced visible abrasion on quartz, but some additional effort was necessary to define scratches made by fines from the Sicily drop zone at Fort Bragg. All of these materials scratched a steel parting tool. This indicates that the hardness was equivalent to about 700–1000 kg/mm^2 on the Vickers scale. A diagram coordinating hardness scales, and showing relative hardness of the specimens, is given in the preceding figure.

The last material received was that from the Australian Army parachute school at Nowra, NSW. This soil differed from the other specimens, as it contained visible plant material, and was of a much darker shade, perhaps because of organic content. It was also unusual in that a second mass mode was found in the particle size range $0.105 > d > 0.053$ mm, in addition to the primary mass mode in the $0.250 > d > 0.125$ mm size class. The fine fraction of this material was sufficiently hard to scratch the photographic plate and the steel tool, but had a "lubricated" feel. This may be attributable to organic coating, and finer, harder material may be present.

Abrasive Properties of Test and Training Site Soils
Relative Hardness of Fine Particle Fraction

AUSTIN W. HOGAN

INTRODUCTION

Interest in the failure of individual parachutes as a function of service life and exposure has a long history (Coskren and Wuester 1989). Segars (1992) reviewed international literature concerning the degradation of stored parachutes and other items made of Nylon 6,6 over time, finding that conclusive evaluation of age deterioration was limited by the lack of initial tests of material properties at the time the parachutes were made. Examination of a sampling of parachutes used by the U.S. Army and the U.S. Forest Service "Smoke jumpers" indicated that suspension lines began to degrade during the first 30 uses.

Laboratory tests by Rodier et al. (1989) confirmed that suspension line degradation was the most common mode of failure, and that this was primarily the result of accumulated contaminants within the suspension lines. Rodier et al. used soil native to the Natick Laboratory as an initial test material, and they found that soils from the drop zones at Yuma Proving Ground, Arizona, and China Lake Naval Weapons Center, California, degraded suspension line strength faster than did the Natick soil. They concluded that inherent geological differences in soil properties would alter the service life of parachutes deployed in varying geographic locales.

My initial report (Hogan 1992) described the physical properties of surface soil specimens from seven paratroop training drop zones, two proving ground cargo chute test areas, and the Natick RDEC drop test pit, all used in the Rodier et al. (1989) experiments. Additional analyses were performed on soil retained within the braid and core of parachute cord test specimens, and test plates exposed near rigger's tables at troop training sites.

The size distribution and clay mineralogy of the specimens were quite different. Surface material from the Saudi and Israeli deserts approached spherical symmetry, while surface materials from test sites at China Lake and Yuma Proving Ground were quite angular. There was a great difference in the mass fraction of fines among the several samples, but all contained material in the range below sieve size. The fraction below sieve size consisted of angular, aspheric particles in all cases, including those specimens that were dominated by nearly spherical particles in the larger size classes.

Several parachute lines that had previously been strained and exposed to local soil materials in the Natick drop test pit were examined for soil residue. The fine fraction of soil penetrated coreless braid, and the smallest particles present were retained within the strands of the braid. Fine particles were found between core strands subjected to a single test drop, although the surface of the exterior braid looked clean.

Individual soil particles caused abrasive damage to delrin test plates in a simple sliding friction test. A more specific experiment was considered necessary to examine the abrasion of textile strands by the smallest size fraction of the soil material. I proposed that a microscopic method of measuring soil particle hardness by relating size classified soil particles to Mohs hardness standards could be used as an input to provide an index of soil abrasion.

This report provides some additional analysis of the size distribution of the fine fraction of the soil samples and the results of scratch hardness experiments to determine the relative hardness of soil grains from the several sites. The effective hardness of some soil specimens, relative to acetal resin (nylon, delrin), was examined in my initial series of experiments. Small quantities of sieve-classified soil were placed on 50-mm-diameter disks machined from delrin bar stock and another disk was placed atop the specimen. Light pressure was applied and the disks moved for about 5 mm in sliding friction contact. The disks were separated and examined for striations by incident light microscopy.

These techniques raised questions, rather than provided conclusions, because the largest particles present dominated the visible results. Goode's (1989) SEM analysis of failed suspension lines, the conclusion of Kodier et al. (1989) that desert soils are more damaging to suspension lines, and the analysis of particles contained within braid and core in my initial report (Hogan 1992) all indicated that the fine particle fraction of the soil did the most damage. So, it is necessary to isolate smaller classes within the fraction that is below sieve size to determine the effective hardness of the fine particles. I hypothesized that experiments with discrete size fractions could speed the establishment of hardness criteria or the creation of a size–hardness factor that could be used to estimate the potential for abrasive damage by soils.

Micro-scale hardness measurements usually employ a stylus of known hardness and area (Tabor 1954, Howell et al. 1959, Rabinowicz 1965, Sarkar 1980), which is used to scratch or indent the surface of the unknown specimen. The works cited above indicate that particles of less than 50 µm in diameter are responsible for the braid and cord abrasion observed. The physical properties of particles in this size range may vary, even though the chemical composition of them may seem quite similar. As mentioned earlier, I proposed that a micro-scale technique, capable of simultaneously examining the hardness of a large number of similarly sized particles, would be most desirable to examine the range of hardnesses encountered. This report describes experiments using this technique.

TECHNIQUE FOR MEASURING THE HARDNESS OF FINE PARTICLES

The hardnesses of metals, alloys and industrial materials are measured by several standardized techniques (Brinnell, Knoop, Rockwell, Vickers), which deform the material surface. A standard sphere, cone or pyramid is pressed against the specimen surface, and the hardness is expressed as the ratio of the applied pressure to the area or depth of surface deformed. Tabor (1954) describes several techniques used to measure the effective hardness of textiles, plastics, polymers and other nonmetallic materials. Nonmetals have a tendency to restore deformation as pressure is released, and larger uncertainties are inherent in nonmetal hardness measurements. Hardness scales and measurement techniques are reviewed by Sarkar (1980), Rabinowicz (1965) Howell et al. (1959) and Tabor (1951, 1954).

The relative hardness of materials can be estimated by relatively simple scratch tests. According to Tabor (1954) the Mohs (1822) hardness scale is the oldest known hardness measuring method and is used to establish the relative hardness of natural materials through their ability to scratch Mohs' defined hardness standard specimens. The Mohs hardness scale has been translated to the Knoop scale by Foster (1967) and to the Brinnell, Rockwell and Vickers scales by Tabor (1954).

The Mohs hardness scale is usually applied by successively attempting to scratch the surface of Mohs standards of ascending hardness with the specimen. The specimen's hardness is then some intermediate value greater than the hardest standard scratched. The Mohs method is generally a two-body comparison as described. The abrasive wear of cordage more likely approaches three-body wear, as described by Rabinowicz (1965). The three-body wear geometry considers a foreign particle confined between two surfaces as the abrasive agent.

I have applied the Mohs scale in a three-body hardness experiment. A small, size-classified quantity of the of the material of unknown hardness is placed on the Mohs standard specimen. A 5-mm-diameter hardwood dowel, truncated at about 30°, is placed in contact with the unknown material and pressure is applied by hand, imbedding the fines in the dowel. The dowel is then moved in a push–pull motion through about 5 mm on the Mohs standard surface; the imbedded unknowns scratch the standard surface if they are sufficiently hard. An additional resistance to motion is provided by abrasive friction when the unknown does scratch the standard, but this "feel" does not uniquely identify scratching of the surface. Each area is examined microscopically for scratches in parallel lines along the push–pull axis. This allows unique identification of multiple, parallel scratches by the unknown, in the presence of randomly oriented scratches that may be already on the standard. A photomicrograph of a scratched quartz standard is given in Figure 1.

It is evident that, if this three-body simulation is

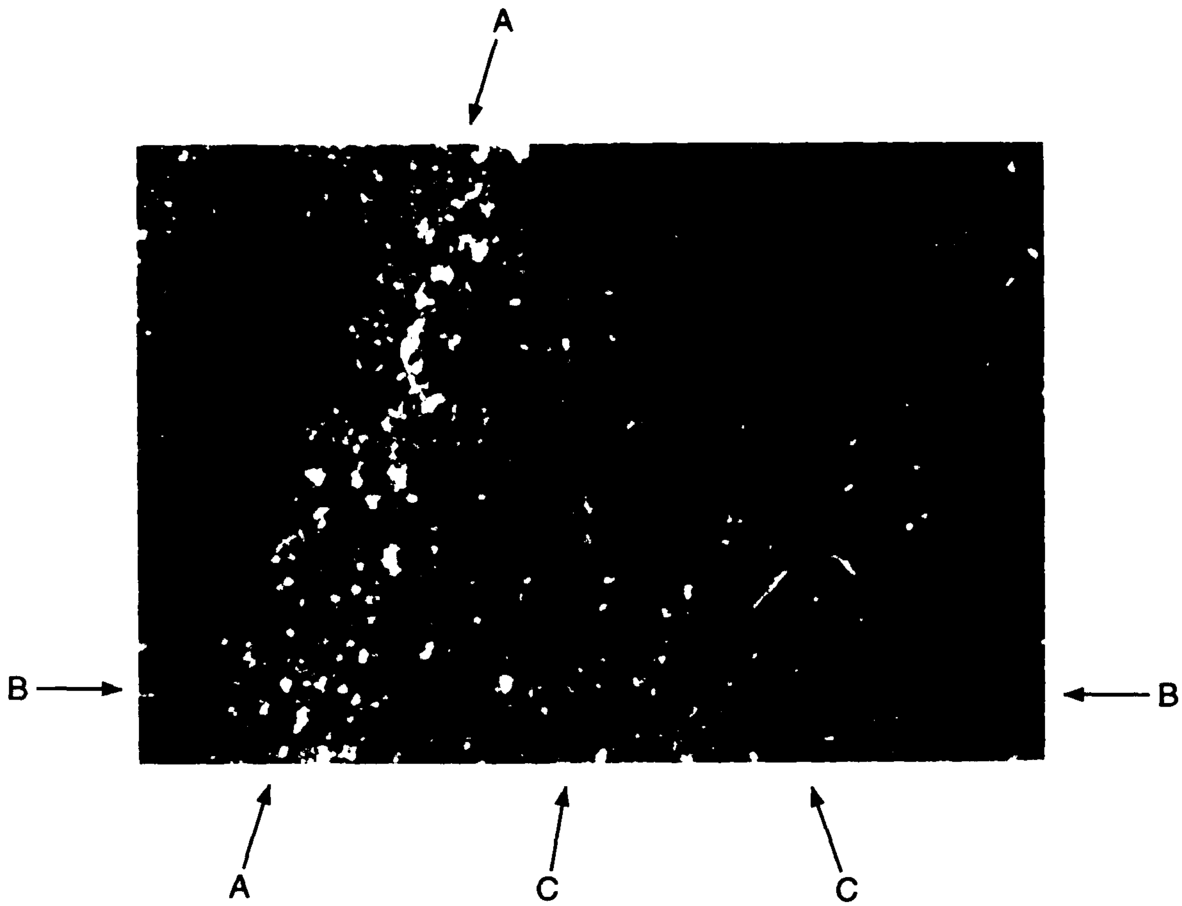


Figure l. Scratches made by fine soil particles on quartz hardness specimen in oblique illumination. Residue of the soil specimen lies along A—A, and striations of the hardness standard lie along B—B. Scratches made by the particles in the standard are nominally normal to the striations in the sector C—C (microphotograph by E. Cortes).

applied using abrasive particles with a large range of diameters, the largest particles will contact the surfaces and prevent abrasion by the smallest particles. This requires that a relatively narrow range of particle diameters be extracted from the whole sample for three-body hardness experiments. This was done through sieve separation of fines, using sieves from both the DIN and USS series to obtain cuts with relatively narrow diameter ranges.

Relatively large (30–50 g) quantities of each soil specimen were first conventionally separated using a 5-cm-diameter frame DIN Prufsieb sieve (1.0, 0.5, 0.25, 0.125 mm) series. The fractions retained by the 0.25- and 0.125-mm screens were resieved, and the total quantity passing 0.125 mm was used for microsieve separation in a 10-cm frame USS sieve (0.105, 0.053, 0.044 mm) series.

The $0.125 > d > 0.105$ mm, $0.053 > d > 0.044$ mm, and 0.044 mm $> d$ separations provided sufficiently narrow diameter ranges for three-body abrasive experiments. The 0.044 mm $> d$ fraction contains the particles approximating the diameters of those removed from within the cordage in the initial experiment. Figure 2 relates equivalent standard grits to the size fractions used. The $0.125 > d > 0.105$ mm separation corresponds approximately to 320 grit; $0.053 > d > 0.044$ mm to 800 grit; and the smallest fraction to 1000 grit. The relative fractions of the mass of submillimeter components of the several soils are shown in Figure 3.

A series of Mohs hardness specimens of sufficient size to permit multiple hardness experiments was obtained from Wards Natural Science Establishment. The specimens were ruled as shown in Figure 4, after gentle surface cleaning. The surfaces were examined microscopically, and the grids coded for later abrasive identification. The hardness specimens are natural materials and do not always present smooth, flat faces for scratch testing. The three-body abrasive experiment requires a minimum area of about 3 × 5 mm to examine each

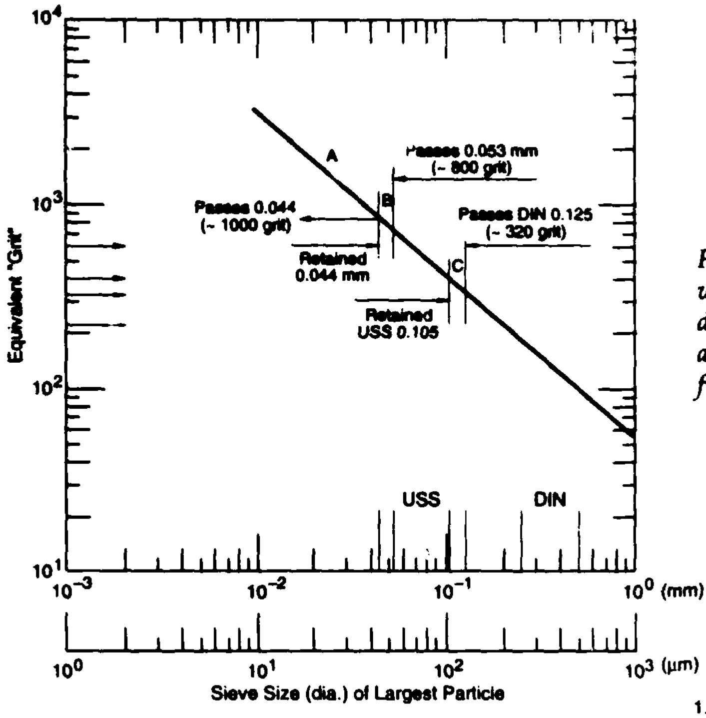


Figure 2. Comparison of standard abrasive grit sizes with sieve sizes. The particles associated with cordage damage correspond in size to 1000-grit commercial abrasives. The letters A, B and C designate the size fractions used in the hardness experiments.

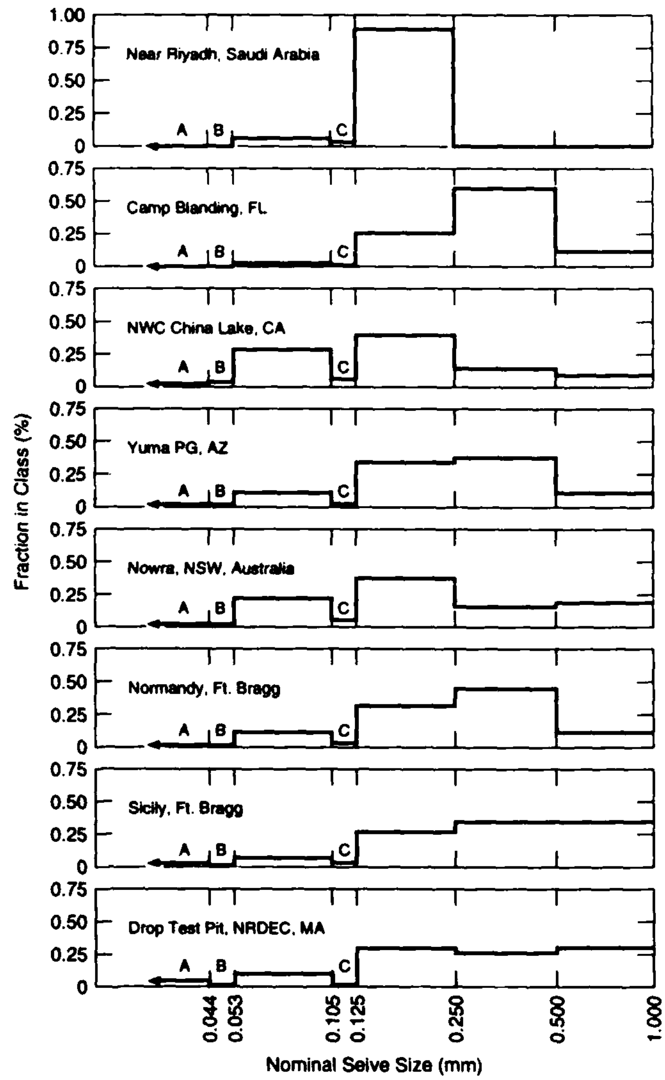
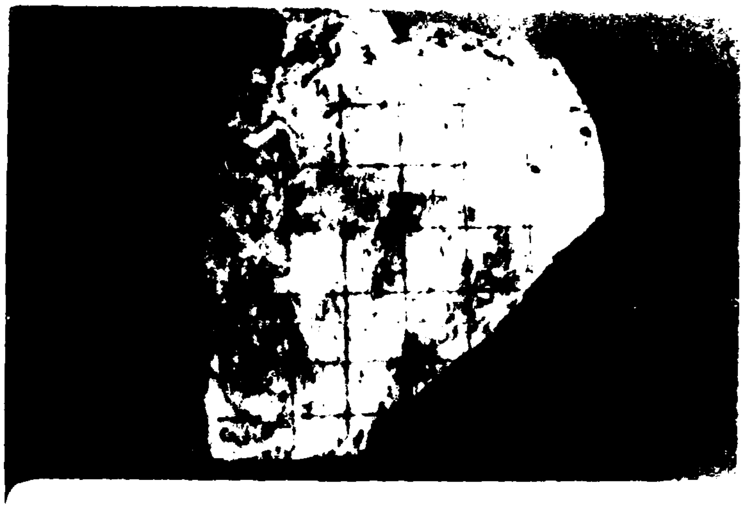
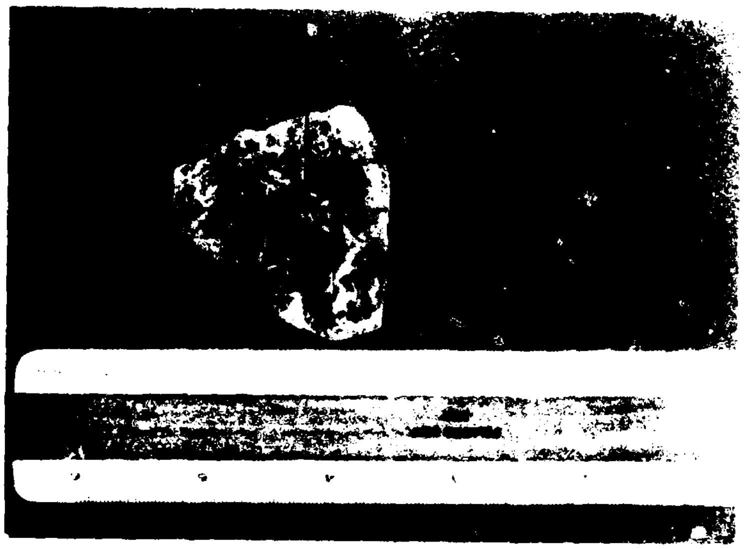


Figure 3. Size distribution by mass of the materials examined. The letters A, B, and C designate the size fractions used in hardness determination, as in Figure 2.



a. Apatite.

b. Quartz



c. Topaz.

Figure 4. Hardness specimens used in experiments. The diversity of surface on natural specimens required systematic application of the abrasive and microscopic verification that abrasion nad occurred (photographs by P. Keene).

Table 1. Comparison of hardness values of various materials on Mohs and Knoop scales (after Foster 1967)

Substance	*Formula*	*Mohs value*	*Knoop value*
Talc	$3MgO\ 4SiO_2\ H_2O$	1	
Gypsum	$CaSO_4\ 2H_2O$	2	32
Cadmium	Cd		37
Silver	Ag		60
Zinc	Zn		119
Calcite	$CaCO_3$	3	135
Fluorite	CaF_2	4	163
Copper	Cu		163
Magnesia	MgO		370
Apatite	$CaF_2\ 3Ca_3(PO_4)_2$	5	430
Nickel	Ni		557
Glass (soda lime)			530
Feldspar (orthoclase)	$K_2O\ Al_2O_3\ 6SiO_2$	6	560
Quartz	SiO_2	7	820
Chromium	Cr		935
Zirconia	ZrO_2		1160
Beryllia	BeO		1250
Topaz	$(AlF)_2SiO_4$	8	1340
Garnet	$Al_2O_3\ 3FeO\ 3SiO_2$		1360
Tungsten carbide alloy	WC, Co		1400–1800
Zirconium boride	ZrB_2		1550
Titanium nitride	TiN	9	1800
Tungsten carbide	WC		1880
Tantalum carbide	TaC		2000
Zirconium carbide	ZrC		2100
Alumina	Al_2O_3		2100
Beryllium carbide	Be_2C		2410
Titanium carbide	TiC		2470
Silicon carbide	SiC		2480
Aluminum boride	AlB		2500
Boron carbide	B_4C		2750
Diamond	C	10	7000

material sample, and it is necessary to use less than ideal curved or striated areas of some specimens to provide sufficient test area. The shape, thickness and varying surface aspect of the Mohs standards also posed certain problems for microscopic examination of the test area. Coaxial incident illumination provided unique identification of surface scratches. Relatively high magnification was necessary to define the scratches in the presence of residual fines when evaluating the hardness of the < 0.044-mm (1000-grit) fraction of the soil specimens. A hand-held field microscope was sufficient to define the scratches made by the $0.125 > d > 0.105$ mm (320 grit) fraction of the soils.

Review of Tabor's works on bearing friction and preliminary experiments with common materials indicated that most of these soil specimens lay in the Mohs 5 to 7 hardness range. The comparison of the Mohs and Knoop hardness scales given by Foster (1967) (Table 1) indicates that the hardness of soda lime ("soft") glass lies just above 5 (apatite) on the Mohs scale. This allowed flat, smooth, 50- × 75-mm photographic plates to be used to establish a lower limit of hardness for the soil specimens. The photographic glass was also used to verify that the three-body abrasive model could be approximated using the screened soil and a hardwood dowel by examining the contact area of the dowel microscopically after applying the grit to the glass surface.

Commercial abrasives are generally harder than 8 (topaz) on the Mohs scale. The topaz hardness specimens used were relatively flat and parallel-faced, facilitating use of three 50- × 50-mm topaz specimens as upper hardness limit.

Hardened tool steels have hardness in the 700- to 1000-kg/mm^2 range, corresponding to Mohs hardness of 5 (apatite) to 7 (quartz). A hardened and ground 10- × 150-mm parting tool was used as a hardness specimen to allow comparison of results to Tabor's description of textile-to-tool wear and friction.

RESULTS OF EXPERIMENTS

Size-classified soil fractions from the Natick RDEC drop test pit, Yuma Proving Ground, China Lake, Camp Blanding, Riyadh, Fort Bragg Normandy Drop Zone, and Fort Bragg Sicily Drop Zone (see Appendix A), as identified earlier (Hogan 1992), were examined for hardness using the methods described above. An additional specimen received late in the program from the Australian Army Parachute School, Nowra, NSW, was also examined in the same manner. This soil differed from the other specimens, as it contained visible plant material, and was of a much darker shade, perhaps because of organic content. It was also unusual in that a second mass mode was found in the particle size range $0.105 > d > 0.053$ mm, in addition to the primary mass mode in the $0.250 > d > 0.125$ mm size class. The fine fraction of this material was sufficiently hard to scratch the photographic plate and the steel tool, but had a "lubricated" feel. This may be attributable to organic coating, and finer, harder material may be present.

About 1 mg of a sieve-classified soil fraction was transferred to the surface of the test specimen. A glass photographic plate was used as the initial specimen in each case, as this quickly established the minimum hardness of the material. All of the soils examined readily marked the soft glass, with the exception of the black fraction of the material found in Camp Blanding fines. This black material is nonmagnetic and is inertially separable from other particles of the same sieve size. It may be graphitic carbon residue from forest or brush fires.

Slightly lesser quantities of size-classified soil were transferred to the surface of a lathe parting tool. The tool had been polished along its long axis with a 220-grit wheel (determined microscopically), so only the $0.125 > d > 0.105$ mm size fraction could be used, making scratches normal to those residual from manufacture. All of the specimens examined scratched the parting tool, although some difficulties were evident in the trial with the Australian specimen. This and other preliminary examinations indicated that these specimens had hardness in the Mohs 6 (Feldspar) to 7 (Quartz) range.

A relatively flat side of a large (Fig. 4a) microcline (Feldspar) standard was laid out on an approximately l-cm grid. Milligram quantities of 0.044 mm $> d$ and $0.125 > d > 0.105$ mm fractions of each sample were applied to alternate sides of individual grid squares. Stereo microscopic examination showed that all of the specimens rapidly eroded the microcline surface. Two smaller (5×5 cm) Mohs 8 (Opal) standards were similarly gridded and examined to define the upper limit of hardness. Very few scratches were observed, indicating that only a few particles of harder substance were present in the examined samples.

This indicates that the specimens examined had hardness comparable to Mohs 7 (Quartz, Fig. 4b). The rock crystal obtained as a Mohs 7 standard had several spalled or choncoidal fractured surfaces, and numerous striations on its surface. It was necessary to select very small surface sectors for application of the soil specimens and to examine the surface with incident light microscopy. The surface striations made application of the $d < 0.044$ fractions quite difficult.

Most "sand" is descended from the weathering of quartz, and an engineering mean hardness value for sand of 800 kg/mm^2 is given by the Vickers scale. Sand is confined to the larger size classes of the particles examined. The finer particles that are able to penetrate and damage cordage are more angular than sand.

The relative hardnesses of the soils examined are compared vs. hardness scales in Figure 5. The ranking is somewhat subjective; it was quite easy to

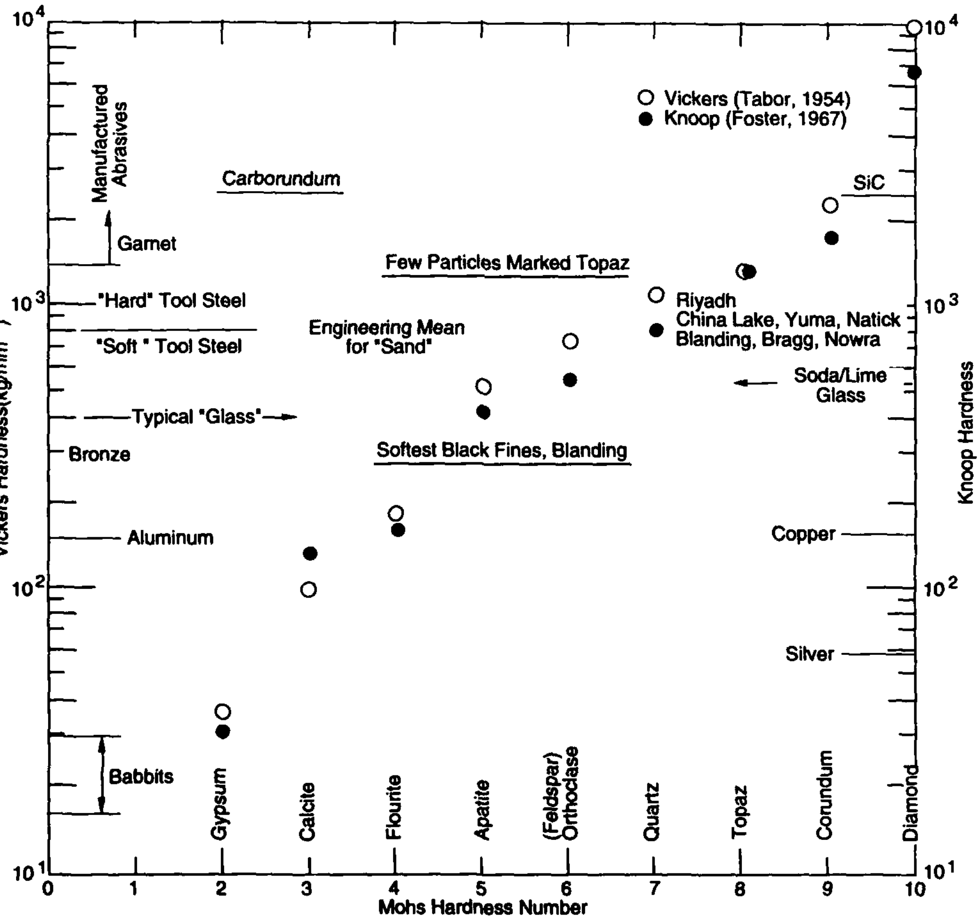


Figure 5. Comparison of Vickers, Knoop and Mohs hardness scales (after Tabor 1954). Hardnesses of common materials are noted on the left, relative to Vickers hardness, and on the right, relative to Knoop hardness. The soils tested are noted corresponding to their relative hardness.

make scratches with the Riyadh fines and quite difficult to scratch adjacent places on the same specimen with the Fort Bragg fines, establishing the "hard" and "soft" limits. The remainder are ranked on a subjective scale based on the degree of difficulty associated with producing visible scratches on the hardness substrates.

DISCUSSION

The hardness of the fraction of soils $d < 0.125$ mm from several test and training areas examined to date approximate that of quartz, "sand" and tool steels. Some harder "contaminants," similar in hardness to garnet, can be present in any specimen, and much softer material made up a significant fraction of fines obtained from Camp Blanding and Nowra. Subjective judgment, feel during application and difficulty in microscopic detection of scratches after application indicate that the "hardest" fines came from Riyadh, and the "softest" from Fort Bragg and Camp Blanding. A composite scale has been prepared in Figure 5 that relates the Vickers and Knoop hardness scales to the Mohs scratch hardness scale. The hardnesses of several materials from the literature are also defined on the axis. The subjective array of hardness of the soil fines examined is plotted.

It should be noted that a certain anomaly, or perhaps internal contradiction, is present here, and some caveats should be considered in interpreting or applying these results. The Mohs scale compares the surfaces of materials on a relative scale that is independent of the size of the specimen, or the pressure applied to produce a surface scratch. The hardness scale relations provided by Tabor are macroscopic, derived from penetration of a sphere or pyramid as a function of pressure applied. Classical research in three-body abrasion shows abrasive wear to diminish with particle size when mean particle size decreases to less than 0.2 mm. A scratch to one-half depth by a 0.2-mm particle would leave a 0.1-mm clearance in which finer particles could circulate without abrading the surface.

The initial work done on this problem showed that the fine particle component of soils penetrated cordage, causing internal abrasion. Larger particles that could produce these clearances were absent, and the abrasion was caused by particles less than 0.05 mm in diameter. The most frequent particle size observed within damaged cordage was $0.03 < d < 0.04$ mm, a size ignored in many past industrial wear and hardness investigations. The fine component was extracted from the whole for these hardness experiments. Size classification allows numerous fine particle faces to be applied to a surface. The small diameter of the individuals results in application of very large contact pressure, many times the initial force.

The cordage applies a classification criterion to the fines it admits. If larger particles were admitted, the pressure applied at the abrasive face would diminish, and no pressure would be applied to the finer members of particle dispersion. This would reproduce the classical wear diminution with size. The very great contact site pressure that can be applied through relatively uniform-sized fine particles apparently reverses this size–wear relation in the case of cordage.

Although there is a notable difference in hardness among the several soils, all of the soils contain a fine component significantly harder than nylon 6,6. The size distribution of all the soils approximates a log–normal distribution (Hinds 1982), and the pertinent size parameters are tabulated in Table 2. The observation of Rodier et al. (1989) that soils from the China Lake and Yuma test sites were especially damaging to cordage is supported by the data, as both sites have a relatively large fraction of the soil smaller than 50 μm.

Table 2. Soil size parameters.

Source	*Median diameter (mm)*	*Geometric standard deviation*	*Fraction less than 50 μm*
Riyadh, Saudi Arabia	0.165	1.3	0.008
Camp Blanding, Florida	0.32	1.5	0.002
China Lake NWC, California	0.165	2.2	0.043
Yuma Proving Ground, Arizona	0.25	1.9	0.028
Nowra, NSW, Australia	0.21	2.8	0.045
Fort Bragg, North Carolina (Normandy drop zone)	0.27	1.9	0.045
Fort Bragg, North Carolina (Sicily drop zone)	0.335	2.1	0.008
Natick, Massachusetts	0.34	2.0	0.019

There may or may not be a general relation among soil size and hardness properties and textile damage. There may be some mechanical and electrostatic factors that facilitate and enhance the adhesion and intrusion of soil particles within cordage. My preliminary experiment did not detect large quantities of soil dust precipitating in a riggers' loft. Films of mass maneuvers with multiple canopy openings show each opening to be accompanied by a dust cloud.* The accelerations of the partially filled canopy apparently generate sufficient force to detach the soil particles from them, although vigorous shakes in the riggers' loft do not.

Several specimens of cordage that had been exposed to soiling during drop tests at Natick were disassembled and examined for internal soil residue. Cords subjected to a single exposure contained observable internal soil deposits. It is difficult to account for movement of soil grains through several strata of strands in a single brief exposure, although electrostatic effects may accelerate the process. Contact electrification among particles of similar size has recently been demonstrated by Horn and Smith (1992), which may account for particle adhesion within the cordage.

CONCLUSIONS

Soil specimens from several test and training sites were examined for particle size distribution and the relative hardness of the fraction smaller than 0.125 mm diameter. There were some relatively soft particles included in specimens from Camp Blanding, Florida, and Nowra, NSW, Australia. Almost all the specimens included a few particles as hard as garnet. The bulk of all specimens had hardness in the range 700–1000 kg/mm (Vickers scale) corresponding to 7 on the Mohs scale. Subjective considerations place specimens from Riyadh, Yuma and China Lake in the greater hardness categories, and those from Fort Bragg and Camp Blanding in the lesser hardness category.

All of the soils examined contained particles in the potentially damaging size classes that are less than 50 μm in diameter. Those from Yuma, China Lake and Nowra contained the largest mass fractions of these.

LITERATURE CITED

Coskren, R.J. and E.A. Wuester (1989) Investigation of the service and age lives of U.S. Army personnel parachutes. American Institute of Aeronautics and Astronautics. AIAA paper 89-0915-CP.

Foster, S. (1967) In *Handbook of Physics and Chemistry*. Chemical Rubber Pub. Co., 46th edition, p. F17.

Goode, P. (1989) Scanning electron microscope evaluation on MIL C 5040 Type II nylon cord. USA Natick Research, Development and Engineering Center, Internal Memo (unpublished).

Hinds, W.C. (1982) *Aerosol Technology*. New York: John Wiley.

Hogan, A.W. (1992) Effects of the abrasiveness of test and training site soils on parachute life. USA Cold Regions Research and Engineering Laboratory, Special Report 92-11.

Horn, R.G. and D.T. Smith (1992) Contact electrification and adhesion between dissimilar materials. *Science*, **26**: 362–364

Howell, N.G., K.W. Mieszkis and D. Tabor (1959) *Friction in Textiles*. New York: Textile Book Publishers (Interscience).

Rabinowicz, E. (1965) *Friction and Wear of Materials*. New York: John Wiley.

Rodier, R.W., E.A. Wuester and J.E. Hall (1989) Personnel parachute age/service life criteria. American Institute of Aeronautics and Astronautics. AIAA paper 89-0916.

Sarkar (1980) *Friction and Wear*. New York: Academic Press.

Segars, R.A. (1992) The degradation of parachutes: age and mechanical wear. USA Natick Research, Development and Engineering Center, Technical Report Natick/TR-92/035.

Tabor, D. (1951) *The Hardness of Metals*. Oxford: Oxford University Press.

Tabor, D. (1954) Mohs hardness scale—A physical interpretation. *Proceedings, Physical Society (London)*, **B67**: 249–257.

*Personal communication with E.A. Wuester, U.S. Army Natick Research, Development and Engineering Center, 1991.

APPENDIX A: SOIL SPECIMENS

These specimens were collected at active training drop zones, at parachute test sites, and in an area typical of those traveled by U.S. forces on the Arabian peninsula. Representative specimens were collected from the surface, sealed in plastic bags, and transported to the laboratory. All spe s were received in a relatively dry condition alyzed without additional drying or conditi g.

Table A1. Identification of surface soil specimens.

ID code		*Collection location*
01/14VI91	Phillips drop zone	Yuma Proving Ground, Arizona
02/14VI91	G4 test area	NWC, China Lake, California
03/14VI91	Test pit	NRDEC, Natick, Massachusetts
04/17VI91	Sicily drop zone	Fort Bragg, North Carolina
05/17VI91	Holland drop zone	Fort Bragg, North Carolina
06/17VI91	Normandy drop zone	Fort Bragg, North Carolina
07/17VI91	Dhahran–Riyadh highway	Saudi Arabia
08/27VI91	Special forces drop zone	Camp Blanding, Florida
09/27VI91	Frazer drop zone	Fort Benning, Georgia
10/28VI91	From coreless braid	NRDEC, Natick, Massachusetts
11/25VII91	Drop zone	South of Tel Aviv, Israel

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The experiment reported here shows that fine soil particles contribute to abrasion, wear and ultimate failure of parachute materials in a manner somewhat analogous to "three-body abrasion" in metals. The "hardness" of the particles collected at several test, training and maneuver areas is examined and scaled to known natural materials and commercial abrasives. The geometric diameters of the soil grains that enter and imbed in the fibers are a primary factor for understanding the abrasion mechanism. In the case of cordage abrasion, the fraction of soil grains less than 0.2 mm was dominant within the strands and among the fibers. The particles were applied to designated surface grids on relatively large (3×3 to 7×7 cm) Mohs hardness specimens, glass photographic plates and steel cutting tools. All of the fine particles abraded glass photographic plates, with the exception of a soft, nonmagnetic, black fraction found in Camp Blanding fines. None of the materials scratched corundum, although it was possible to make a few scratches in Topaz with almost all specimens. The general upper limit of hardness was similar to that of quartz, which showed some detectable abrasion by five specimens. Fines from the Riyadh, Saudi Arabia, area easily scratched quartz, and this material is the hardest measured to date.

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