EARTH ANALOGUE TESTING AND ANALYSIS OF MARTIAN DURICRUST PROPERTIES¹

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Abstract

Previous and current Mars rover missions have noted a nearly ubiquitous presence of duricrusts on the planet surface. Duricrusts are thin, brittle layers of cemented regolith that cover the underlying terrain. In some cases, the duricrust hides safe, or relatively safe, soil. However, as was observed by both Mars exploration rovers, Spirit and Opportunity, such crusts can also hide loose, untrafficable terrain, leading to Spirit becoming permanently incapacitated in 2009. Whilst several reports of the Martian surface have indicated the presence of duricrusts, none have been able to provide details on the physical properties of the material, which may indicate the level of safe traversability of duricrust terrains. This paper presents the findings of testing terrestrially-created duricrusts with simulated Martian soil properties, in order to determine the properties of such duricrusts and to discover what level of hazard that they may represent. Combinations of elements that have been observed in the Martian soil were used as the basis for forming the laboratory-created duricrusts. Variations on duricrust thickness, water content, and the iron oxide compound were investigated. As was observed throughout the testing process, duricrusts behave in a rather brittle fashion and are easily destroyed by low surface pressures. This indicates that duricrusts are not safe for traversing and they present a definite hazard for travelling on the Martian landscape when utilising only visual terrain classification, as the surface appearance is not necessarily representative of what may be lying beneath.

Research highlights: ► Fabrication of artificial Mars duricrusts based on Mars geology. ► Empirical testing and evaluation of artificial duricrust mechanical properties. ► Testing of safe rover trafficability using standard geotechnical site survey methods. ► Useful for full sensor testing (e.g. Ground Penetrating Radar, soil sampling systems) or as a physical analogue only (e.g. rover sinkage experiments).

Keywords: Planetary rovers, Safe trafficability, Duricrust, Terrain classification, Cone Penetrometer

1. Introduction

Mars is an intriguing destination within the solar system as a possible host for past life or the presence of life-essential building blocks. This makes our close neighbour an enticing candidate for remote exploration. For the past 50 years, several missions have been sent to Mars (Fig. 1) to collect data in the hope of further our understanding of the universe, each with varying success. The NASA Mariner missions during the mid-1960's brought the first close-up images of the Martian surface from orbit, along with atmospheric and temperature data. Additional orbiter data were provided by the U.S.S.R. "Mars" missions in the early 1970's, along with a successful landing on the surface in 1971. The Mars 3 lander was equipped with sensor equipment and an autonomous rover (PROP-M), which was a very promising mission [1]. Unfortunately, the lander was only operational for about 14.5s before ceasing transmissions [2].

In the mid-to-late 1970's the NASA Viking missions successfully landed on the planet surface and reported on chemical composition of the soil [4]. It also provided the first hints at possible former life on Mars. More recently, several rover, lander, and orbiter missions have successfully reached Mars. The modern rovers and landers: Pathfinder, Spirit, Opportunity, Phoenix, and most-recently, Curiosity have so far travelled more than 70km [5,6], combined, analysing the Martian atmosphere, soil, and rocks to gather scientific data, specifically concerning the possible existence of past life on the planet. Each of these missions has directly

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or indirectly experienced sulphate salt-based duricrusts [3] across the surface of Mars during their missions (Fig. 1). Throughout this same time period, numerous other (unfortunately unsuccessful) attempts also have been made by various countries and agencies. Due to their longer-than-expected operational performance, the NASA Mars Exploration Rovers (MER) Spirit and Opportunity have been incredibly successful. Initially intended for 90-day missions, both of the rovers have been on Mars for just over 10 years, with Opportunity still operational and gathering data. In 2005, however, Opportunity became lodged in the soft soil underlying a thin surface duricrust at “Purgatory Dune” [5]. As seen in Fig. 2, there is a thin duricrust layer on the surface that obscures the underlying regolith, which for this area is of a different composition than the surface material. This obscuring effect is a danger when navigating by vision-based means for terrain classification, since it is unknown what type of terrain is actually present beneath the surface.

Figure 1. Martian elevation map showing the successful lander and rover mission touchdown sites [2].

Figure 2. MER Opportunity stuck at Purgatory Dune in 2005 (left – Front Hazcam, Sol 449) and retreating after becoming free (right – Navigation Camera, Sol 491). Note the colour of the regolith in the wheel tracks, indicative of different soil beneath the thin duricrust [5].

In May 2009, Spirit suffered a similar “embedding event” and became permanently lodged in the soft underlying soil at a feature named Home Plate in the region called “Troy” [6]. At that time, Spirit was operating with only five of its six wheel modules functioning, which presented locomotion issues. This became a larger issue when the rover encountered extremely loose, white soil hidden below the thin surface crust. Although operators attempted to drive the rover back out of the hazardous region, the limited mobility of five wheels and inability of the rover to gain traction on the very fine soil prevented extraction. During further analysis, it was discovered that the rover was likely to be high-centred on a small mound of rocks, which further hindered the extraction efforts. Despite months of planning with Earth-based simulation attempts, Spirit was reported as permanently embedded at Home Plate. Less than a full year later in 2010, Spirit’s power levels dropped and the rover went silent, ending its mission.

For each of these cases, the initial embedding event was caused by the inability of the rovers to perceive the terrain beneath the thin surface duricrust layer. Since the rovers relied on visual assessment and characterisation of the terrain, which appeared similar to surrounding areas, they were unaware of the hazards. Although the duricrusts could not support the mass of the rovers, the thin, brittle layers were sufficient to support, and be formed by, wind-blown surface dust and small soil particles (aeolian sediment transport), which contributed to the camouflaging effort. When such duricrusts conceal loose soil underneath, a hazard exists; although, it is also possible for the duricrusts to form on more solid layers, such as bedrock. Such visual means of estimating soil properties, although rapid, have shown themselves to be insufficient for accurately identifying safe and unsafe terrain in environments where concealing duricrusts are present. Instead, direct-sensing techniques, such as cone penetrometer, dynamic plate, and bevameter testing provide more accurate and useful indications of sub-surface terrain conditions [7]. Each of these example methods penetrates or impacts the terrain to determine sub-surface properties, such as load bearing capabilities, which allows for a reliable assessment of the ability for the soil to support a rover.

As mentioned above, duricrusts are relatively thin layers of indurated soil that seem to ubiquitously cover the surface of Mars, according to several published observations of the planet [3,8-10]. There is still some speculation as to the exact formation process of these crusts on the Martian surface, although it is held that the most-likely cause is due to microscopic layers of moisture on the surface of aeolian particles. This moisture comprises dissolved salts and other compounds that create weak bonds through precipitation of minerals through evaporation or other processes with neighbouring particles. As more material is deposited on existing cemented material, the layer becomes thicker. Since this process involves wind-deposited material, the crusts are extremely weak and prone to fracture and crumbling by the same wind. As such, many of the identified duricrusts on the Martian surface are relatively thin [3,12,13] (Fig. 3).

Figure 3: Martian terrain as viewed by the MER Spirit Pancam (Sol 2190). Note the cracked and crumbled surface thin duricrust and the loose soil beneath [13].

Figure 4: Composition of Martian surface materials. Circles, squares, stars and triangles represent Spirit, Opportunity, Pathfinder and Viking data, respectively. MER data: black (rocks), red (bright dust), blue (dark soil), cyan (haematitic soils at Meridiani, high-sulphur trench interiors at Gusev), green (other soils). Pathfinder data in magenta and green represent independent fits of the same data; black is the sulphur-free rock composition. Viking 1 and 2 data are plotted in yellow and magenta, respectively. Renormalization uses iron as FeO and average Gusev values for elements not measured. Approximate error bars representing the uncertainty shown for MER (‘M’), Pathfinder (‘P’), and Viking (‘V’) data [17].

Another formation method for duricrusts would be for ground moisture, which contains similar dissolved salts and other compounds, to evaporate and leave behind a weakly cemented soil surface. Although this is a common occurrence on Earth, where ground moisture is abundant, the low moisture content of Mars may make this formation method slightly less likely. These two methodologies are both speculative, however, and neither method has been conclusively shown nor disproved [14].

Some support for the relative weakness of these duricrusts can be seen by the low moisture content on Mars. As indicated by several sources, the soil and atmospheric water content is only between 2 – 11%. According to the data generated by the Viking lander missions, a very low water content was discovered, approximately 2 – 4%, although the Viking instruments were not specifically calibrated for such tests [15]. Later reports show evidence of higher water content on the planet, citing 10% relative humidity from Viking mission orbiter data [16] and 9 – 11% as predicted by the hydrogen content observed by the Odyssey orbiter [3]. These small quantities of moisture can only appear to be capable of supporting small amounts of dissolved salts, which in turn form very weak duricrusts. The laboratory experiments, described in the following sections, support this observation by showing a clear relationship between duricrust strength and initial moisture content.

To mitigate the risks to rover mobility on Mars and hence allow higher rover speeds, the concept of using a light, highly mobile scout rover to define a safe path for a heavier mother rover was investigated during the FP7 FASTER project [7]. The key to achieving these objectives was to design a rover that is sufficiently nimble to be able to traverse a wide variety of terrains and able to get out of trouble. The FASTER team designed the rover shown in Fig. 5 which uses the sinkage of test feet on the front legged wheels to determine trafficability while moving. However, a duricrust of variable thickness may still pose a risk to the mother rover. At the locations where the test feet touch down a duricrust may have sufficient strength to support them and hence a trafficable surface will be reported back to the mother rover. The duricrust however, may not have sufficient strength to support the mother rover over its overall larger footprint. If the material under the duricrust is sufficiently loose, as at Troy in the case of the MER Rover Spirit, the mother rover could break through the duricrust and become trapped. Ideally the nature and thickness of any duricrusts traversed by the scout need to be investigated while moving forward. On Earth this problem could be solved using high frequency Ground Penetrating Radar (GPR) but there is insufficient knowledge at this

time of the dielectric properties of the Martian regolith to have any confidence that this geophysical method would be able to resolve the interface between a duricrust and the underlying soil. The only alternative is a direct method of investigation. A Dynamic Cone Penetrometer was chosen as there is a lot of experience using this type of device on Earth for geotechnical site investigations for profiling the subsurface as well as measuring geotechnical design parameters empirically. A miniature DCP was designed to be compatible with the volume, mass and power budgets of the scout rover.

Figure 5: FASTER scout rover Coyote II equipped with full sensor suite, including its soil sensor system payload developed by University of Surrey. (Photo: Roland Sonsalla, DFKI GmbH).

In order to test how effective the DCP is at delineating duricrusts, as well as measuring their strength, it was necessary to set up a series of Earth-analogue laboratory experiments. These experiments involved creating duricrusts of different composition and thickness. The composition of the duricrusts in terms of chemistry and water content were designed as far as possible to match what we know about those on Mars. To simplify the experimental set up, the DCP used had the same geometry and dimensions as that fitted to the scout rover but the energy was delivered by a drop weight instead of an artificially accelerated mass. The energy delivered at the cone was designed to be the same for both types of DCP.

The manufacture of duricrusts for the small-scale experiments described in this paper proved to be reasonably straightforward and cost effective. However, when scaling the experiments up to full-size for use with rovers, problems in terms of cost and difficulties in creating the required environment for duricrust development were foreseen. This resulted in further small-scale experiments being carried out with more readily available materials that are more easy and cheaper to use at a larger scale but would behave in the same manner as the more realistic duricrusts. The material chosen for this purpose was Ordinary Portland Cement (OPC).

This paper describes the creation of Martian duricrust simulants of various thickness and the effectiveness of the DCP in detecting them and determining trafficability. The paper also examines the practicalities in scaling the duricrust manufacture up to a scale that would be suitable for testing full-scale rovers.

2. Duricrust Creation

To test the physical characteristics of Martian duricrusts to support traversing rovers, artificial duricrusts were created in a laboratory setting. Many of the past remote missions to Mars have identified the chemical composition of the Martian soil at several locations on the planet. Yen et al. [17] compiled much of these

data beginning with the early Viking missions of the 1970s and Ruff et al. [18] focused on the NASA MER Spirit and Opportunity missions around Gusev crater and Meridiani Planum. These data reflected the observed compositions of rocks and soils on the surface, identifying nearly a dozen notable chemical compounds and mineralogical components (Fig. 4). The soil content is also important for in-situ resource utilisation, which would be essential to prolonged habitation of the planet [21], and sample-return missions are being planned to further advance our understanding of the Mars (and its moons) soil properties and chemical composition [22].

Due to the extensive nature of these analyses, a subset of chemical compounds was chosen to create simulated duricrust compositions in a laboratory environment. Similarly, the analysis of the ‘bright dust’ portion of the terrain was selected to represent the artificial duricrusts. These selections led to the following elements and proportions used for the experiments presented in this paper (Table 1). The lesser abundant compounds identified in the Martian surface were omitted from these trials and the main compound amounts were normalised based on their weighted presence in the soil. It should be noted that although there is a column labelled ‘Fe’, two types of iron oxide were used during the experiments: magnetite (Fe_3O_4) and haematite (Fe_2O_3). Each oxide was used during different experiments since each of these compounds have been found in Martian soil. For some of the experiments an even mixture of both oxides was also used. The oxides used for each test will be clearly identified in the presented data. The iron oxides, both magnetite and haematite, and the aluminium components were sourced as fine, pure powders.

The magnesium sulphate was purchased as food-grade Epsom salts and appeared as small crystals (<3mm), which were pulverised prior to use. These elements were measured by mass based on their identified proportions (Table 1) and combined thoroughly using a hand rake to form a dry mixture. The resulting dry mixture was then incorporated with the silicon as SiO_2 in the form of sand.

The silicon component comprised a relatively fine (~100-212 μm), sub-angular sand acquired from wind-swept dunes at West Wittering Beach in the south of England. This soil simulant was dubbed SSC-3 (Fig. 6). The sand was chosen for its grain size and shape, being similar to some soil particulates observed on the Martian surface around Gusev crater [19], and also for its availability in bulk. Laboratory analysis of SSC-3 was conducted and found the soil simulant to have a rather narrow selection of grain size, which eliminated the need for extensive processing prior to its use in the duricrust experiments. This uniform grading of the simulant is a characteristic of aeolian sands, such as those found in the Martian surface regolith.

Table 1: Artificial duricrust compounds and mass proportions used for laboratory experimentation

Si (%)	Fe (%)	MgSO ₄ (%)	Al (%)
52.2	19.8	17.3	10.8

Figure 6: SSC-3 soil simulant analysis and images. a) Sieve analysis results showing that about 98% passes the 212 μm sieve; 35% passes the 150 μm sieve; 12% passes the 125 μm sieve; and <4% passes the 106 μm sieve. These results show that nearly all of the naturally-occurring SSC-3 simulant has particle sizes in the range of 100-212 μm . b) 1x image of SSC-3 with different particles identified by size. c) 33x microscope image of SSC-3. d) 400x microscope image of SSC-3.

Once the dry mixing process was complete, in a single batch for a series of six samples (for homogeneity of the mixture amongst the trial set), the mixture was applied to the surface of a set of 9L buckets (Fig. 7, left) partially filled with loose SSC-3 (approximately 1.45g/cc, roughly the loosest natural state for the simulant with a density range of about 1.42g/cc – 1.62 g/cc). The base-layer SSC-3 soil was poured into the buckets from a height of $\geq 0.5\text{m}$, allowing the soil particles to achieve terminal velocity and resulting in the desired low density [20]. The density of the base-level soil was calculated as: density = mass / volume.

The dry duricrust mixture was applied to the surface of the SSC-3 simulant in 4-6 layers by gently sprinkling the mixture onto the prepared loose simulant in order to achieve a relatively uniform-thickness layer. After each layer was applied, the duricrust mixture was hydrated using distilled water in a fine-sprayed mist. The amount of water dispensed per layer was calculated to have a desired final percentage of water, by mass, relative to the duricrust mixture. The amount of water applied and the duricrust thickness were recorded for each sample preparation.

Samples were typically prepared as two sets of three, where each set had similar water content and duricrust thickness. After preparation, the samples were placed under a plastic shroud in an area with a dehumidifier at room temperature (Fig. 7, right). The samples were left for 4-7 days in order to ensure that the applied, and general atmospheric, water had evaporated, allowing the duricrust to form a weakly cemented layer atop the loose SSC-3 simulant. It was found experimentally, that at least four days were required for the entirety of the duricrust to cure. Longer durations were sometimes used due to time availabilities, but it was noted that longer curing times didn't affect the behaviour and performance of the duricrusts; that is, once the duricrust was cured, additional resting time did not alter its physical characteristics.

Figure 7: Freshly-prepared bucket sample using red Fe_2O_3 iron oxide (left). Several prepared samples using black Fe_3O_4 iron oxide curing under the plastic shroud with a dehumidifier (right).

Due to financial constraints, multiple components, and time required to prepare duricrust analogues using the elements identified in the Martian soil, alternative duricrust creation methods were investigated. Beyond the iron oxide experiments, an additional 12 tests were performed using Ordinary Portland Cement (OPC) as the simulant binding agent. These tests were done in order to find a similar physical analogue to the Martian duricrusts that were created in the main portion of this research. Two different proportions of cement were added to SSC-3 as a dry mixture with soil:cement ratios of 50:1 and 25:1. As before with the iron oxide experiments, the dry mixture was applied to the surface of low-density SSC-3 in multiple layers, with each layer prompting water application with a spray bottle filled with distilled water. Variations in the number of layers (4, 6, or 8), duricrust thickness (9 – 24mm), and water content (ranging from 5.66 – 32.75%) comprised the experimental features that were altered.

3. Earth Analogue Experimental Setup

Duricrust samples were prepared in 9L buckets using loose SSC-3 soil simulant as the substructure and duricrusts formed on top of this layer, as described in Section 2. A variety of combinations of iron oxide type, duricrust thickness, and % water content was used (Fig. 8). Due to the early, informal trials that showed Fe_3O_4 to produce stronger duricrusts than Fe_2O_3 , more emphasis was placed on this iron oxide. It was hoped

that a notable load-bearing duricrust could be created as a result of these experiments, in addition to quantifying some of the duricrust physical properties.

Strength of the formulated duricrusts was determined as the apparent soil density, as compared to natural SSC-3, and it was measured by use of a dropped-mass Dynamic Cone Penetrometer (DCP) (Fig. 9). This device was empirically calibrated to the range of natural densities found using the SSC-3 soil simulant (approximately 1.42g/cc – 1.62 g/cc). Penetration-per-Impact and volumetric soil density data were recorded and a curve was fitted for use as the equation to derive density from the depth of each impact (Fig. 10). Note that each of the data points shown in Fig. 10 are averaged values of five experiments performed at each general density: low (about 1.47g/cc); medium (about 1.52g/cc); and high (about 1.69g/cc).

Figure 8: Duricrust experiment criteria for the 33 trials, sorted by iron oxide formulation: pure Fe_3O_4 , a mixture of 50% Fe_2O_3 and 50% Fe_3O_4 , and pure Fe_2O_3 .

Figure 9: Dynamic Cone Penetrometer (DCP) in use testing a duricrust sample (left). Photo of the DCP with labelled parts (right).

Figure 10: Depth of Penetration vs. Soil Density for the SSC-3 soil simulant as measured by DCP.

The cone design of the DCP was based closely on one of the ASTM standard cone penetrometers, which has a cone diameter of 35.7mm and an interior cone angle of 60°. Given the similarity in design, it was planned that other existing, terrestrial, analysis methods could be employed, if needed. DCP specifications are listed below in Table 2. DCP Penetration-per-Impact values and SSC-3 volumetric soil density values were averaged over a set of twelve calibration samples of varying SSC-3 densities: 3 low; 3 medium; and 3 high, in order to create the six soil density-from-depth algorithms. Due to their unique behaviours, a separate algorithm was used for each of the first five impacts and an additional algorithm for the self-weight (zeroth) sinkage (Table 3).

Table 2: DCP device specifications

Total mass	Drop mass (m)	Drop height (h)	Stopping Distance (s)	Impact Force (F)	Cone Diameter
1.37 kg	0.553 kg	0.22 m	0.00265 m	237.43 N	30 mm

Table 3: DCP algorithms for converting Penetration-per-Impact sinkage to SSC-3 soil density

Impact No.	Depth	Density
0	$\leq 37.875\text{mm}$	$0.0140 \cdot \text{depth} + 2.0490$
	$> 37.875\text{mm}$	$0.0014 \cdot \text{depth} + 1.5716$
1	$\leq 31.000\text{mm}$	$0.0113 \cdot \text{depth} + 1.8693$
	$> 31.000\text{mm}$	$0.0026 \cdot \text{depth} + 1.5986$
2	$\leq 15.250\text{mm}$	$0.0194 \cdot \text{depth} + 1.8142$
	$> 15.250\text{mm}$	$0.0055 \cdot \text{depth} + 1.6021$
3	$\leq 13.000\text{mm}$	$0.0309 \cdot \text{depth} + 2.0490$
	$> 13.000\text{mm}$	$0.0070 \cdot \text{depth} + 1.6090$
4	$\leq 10.000\text{mm}$	$0.0324 \cdot \text{depth} + 1.8417$
	$> 10.000\text{mm}$	$0.0059 \cdot \text{depth} + 1.5767$
5	$\leq 8.250\text{mm}$	$0.0523 \cdot \text{depth} + 1.9495$
	$> 8.250\text{mm}$	$0.0042 \cdot \text{depth} + 1.5529$

Each measurement cycle began with the self-weight assessment where the DCP was gently placed onto the soil surface and allowed to sink under its own weight, with no impact or external downward force applied. The dropped-mass impact hammer was then raised to the height of the shaft collar and then released with the guide rod of the DCP allowing it to freely move vertically. This impact process was repeated for approximately 20 impacts, or until the bottom of the sample bucket was reached. Although the DCP was driven to the bottom of the sample buckets, only the first five impacts were used to gauge the density of the duricrust or underlying soil, as it was shown during experimentation that repeated impacts produced indistinguishable differences between varying soil densities after this point (Fig. 13). During each experiment, the cycle of impact was recorded to video and photographs were captured after each impact. The self-weight and first seven impacts of a Fe_2O_3 sample are shown in Fig. 11. After each experiment was performed, the duricrusts were sectioned for analysis and portions were kept in storage for later illustrative purposes (Fig. 12).

Figure 11: Dynamic Cone Penetrometer (DCP) impacts on a prepared duricrust sample comprising Fe_2O_3 during the self-weight penetration, 0, and the first seven impacts, 1 – 7. The duricrust had a thickness of 11mm and was created with a water content of 22.23%. This sample presented a relatively strong duricrust as noted by the DCP requiring four impacts to completely penetrate the crust. The self-weight penetration was very small at only 2mm. Impacts #1 and #2 show the DCP still within the crust. Impact #3 shows the DCP tip exiting the duricrust whilst the body remained within the crust thickness. Impacts #4 – #7 (not shown) represented the DCP body completely beyond the crust, with minimal disturbance to the surface.

Figure 12: Post-experiment duricrust analysis of two Fe_2O_3 samples. (left) 8mm crust thickness with 9.06% water added by mass. (right) 8mm crust thickness with 39.24% water added by mass. The lower water content sample, left, produced a weak, crumbly crust and the higher water content sample, right, produced a strong, solid crust.

4. Earth Analogue Experimental Results

Data from the duricrust experiments was captured and combined into two main formats for analysis: Penetration-per-Impact (Fig. 13), where the self-weight and individual sinkage values for each impact were plotted; and Total Depth of Penetration (Fig. 16), where the accumulative total sinkage of the DCP was shown versus the number of impacts.

The DCP Penetration-per-Impact graph (Fig. 13) shows extremely unique information amongst the samples for the self-weight sinkage and the first 4 – 5 impacts. The Penetration-per-Impact beyond this point generally becomes quite similar for each of the samples, regardless of duricrust preparation. This is due to DCP cone proceeding beneath the duricrust for most of the samples, where the underlying soil preparation is nearly identical. However, for SSC-3 preparations where the soil density varied, as was the case during the DCP calibration experiments, the Penetration-per-Impact still remained similar throughout the test beyond the fifth impact. This is due to the loading effects of the soil above the DCP cone having a greater effect on penetration than the density of the soil local to the cone itself. Because of this, all density calculations only considered the self-weight and first five impacts.

What is most noteworthy in Fig. 13 is the great disparity in the self-weight sinkage values, ranging from 0mm – 42mm and equally broad in values are the depths for the first impact. In each of these cases, the duricrust strength had a leading influence. Although higher water content led to stronger duricrusts, the thickness of the crust also played a key role. Strong, thick duricrusts withstood repeated impacts before allowing the DCP cone to entire pass beyond, as is shown for sample Fe_3O_4 , D5b-3, 23mm, 16.46% (Fig. 14, purple line with x-shaped markers). This sample began with a low self-weight penetration of only 3mm and the first four impacts were: 7mm, 7mm, 6mm, and 6mm, respectively. It was only until Impact #5, with a Penetration-per-Impact of 11mm that the entire DCP cone was nearly beyond the duricrust.

Figure 13: DCP Penetration-per-Impact graphs showing all 33 of the iron oxide duricrust experiments, indicating duricrust thickness and water content, and sorted by water content. Note that around Impact #5, each of the trials behaves similarly for the remaining impacts. This similarity of Penetration-per-Impact is due to the relatively-common soil pressure acting above the DCP cone, and the duricrust is no longer a factor in the DCP penetration.

In comparison, other samples with noticeably weak duricrusts showed signs of failure beginning with the self-weight sinkage. An extreme example was sample Fe₃O₄, D1d-2, 9mm, 3.96% (Fig. 14, fuchsia line with triangle markers). This experiment began with the highest self-weight sinkage of 42mm and continued with high sinkage values for the following impacts. The depths of these initial impacts are about 1/2 – 2/3 of those found for SSC-3 of similar density as the underlying soil, but without the duricrust. This shows that although the duricrust was easily penetrated, it did have an effect on the penetration of the DCP. In some experiments, the duricrust fractured quickly and shards of crust preceded the DCP cone during penetration, resulting in somewhat misleadingly lower Penetration-per-Impact values.

Figure 14: DCP Penetration-per-Impact subsets. The increase in values from impact #5 through #8 for D5b-3 is initiated by the DCP fully penetrating the lower limit of the duricrust. D1d-2 showed the duricrust failing from the onset, such that there is monotonically decreasing values through the trial. D1-5 presented a strong but brittle duricrust, as evidenced by the low self-weight penetration and much higher subsequent values. The numbered sections correspond to DCP penetration stages, as in Fig. 15. D1d-2 did not experience Stages 1-2, beginning directly with Stage 3; and D1-5 did not exhibit Stage 2.

Figure 15: The four DCP penetration stages through the duricrust layer. 1) DCP cone tip remains on top of or within the duricrust layer. 2) DCP cone tip has proceeded beyond the duricrust layer, but the full cone has not yet entered the duricrust. 3) DCP cone tip has proceeded beyond the duricrust layer, but the body of the cone is still within the duricrust. 4) DCP cone has fully penetrated the duricrust layer. These four stages, or a subset thereof, can be seen best in the variation of the plot curves in Fig. 16.

Figure 16 shows the Total Depth of Penetration results for the duricrust experiments. Although this graph is quite dense, it presents two notable trends in the behaviour of the samples: those samples whose duricrust presented a difficulty or reduced ease of penetration (Fig. 16, label 1); and those whose duricrust presented little or no resistance (Fig. 16, label 2).

The compound curves of Fig. 16 (label 1) show the self-weight sinkage leaving only the DCP cone tip slightly penetrating the duricrust (Fig. 15, 1) and requiring several impacts for the full cone to enter the crust layer (Fig. 15, 2 and 3) before finally penetrating the duricrust completely (Fig. 15, 4). This is illustrated by a low initial penetration and gradually-increasing Penetration-per-Impact values. The change in the plot curves from a downward arc to an upward one represents the point where the entire cone had travelled beyond the duricrust and only encountered the loose SSC-3 simulant beneath.

Figure 16: DCP Total Depth of Penetration graph showing all 33 of the iron oxide duricrust experiments, indicating duricrust thickness and water content. The compound curves (1 – downward arc then upward arc) of the upper lines indicate the noted effect of the duricrust for those tests. Simple curves (2 - upward arc only) of the lower lines indicate that the duricrust was not well observed or that it failed early in the testing, either due to a low water content or a small crust thickness.

Weak duricrusts behaved in one of two ways. Either the crust was generally very weakly cemented, in which case the DCP quickly progressed to Fig. 15, 3 or Fig. 15, 4, as the duricrust could not withstand the self-weight and early impacts of the DCP. The other case was where the duricrust may have been more strongly cemented, however it was too thin and brittle to support the DCP and rapidly shattered. For the first scenario, the DCP easily penetrated the sample and the data curves appeared similar to those experienced when no duricrust was present (e.g. Fe₃O₄, D1d-2, 9mm, 3.96%, Fig. 14). The second case, where the crust was

simply too thin, can be seen in examples such as Fe_2O_3 , D1-5, 8mm, 39.24% (most clearly shown in Fig. 14, green line with horizontal bar markers). Despite the high-water content of this sample, which generally resulted in stronger duricrusts, the thinness of the layer was insufficient to resist the DCP.

Following the iron oxide experiments, a dozen tests were performed using Ordinary Portland Cement (OPC) as the duricrust binding agent in order to find a suitable physical analogue with similar strength and density characteristics as those found with the recreated Martian duricrusts. These experiments were performed to test the feasibility of a low-cost, easy-to-fabricate alternative (e.g. OPC) that could be applied to larger-scale tests with actual rover platforms, where only the physical behaviour of the soil needed to be replicated (i.e. suitable for rover trafficability testing, but not ground-penetrating radar). For initial tests, a 50:1 mixture of sand:cement was used. Two such experiments were performed, one where water was applied to each layer of the mixture as droplets of distilled water, and another used the fine-sprayed mist from the previous experiments. Later experiments used a 25:1 ratio of sand:cement in order to produce a stronger duricrust, since the initial crusts proved to be too weak: either too loose and crumbly; or too brittle. The higher cement content of the later experiments formed more resilient duricrusts, which seemed to behave similarly to those Martian duricrust analogues that had a moderate thickness and also had a moderate-heavy water content.

Figure 17: DCP Penetration-per-Impact graph showing the 12 Ordinary Portland Cement duricrust experiments, indicating duricrust thickness and water content. Note that around Impact #5, each of the trials behaves similarly for the remaining impacts, just as they had for the iron oxide experiments. This similarity of Penetration-per-Impact is due to the relatively-common soil pressure acting above the DCP cone tip, and the duricrust is no longer a factor in the DCP penetration.

Figures 17 and 18 show the Penetration-per-Impact, Total Penetration Depth, and Effective Soil Density data, respectively, for these Ordinary Portland Cement trials. It can be seen from these data that the artificial duricrusts constructed with the cement binding agent behaved similarly to the mid-level Martian duricrust analogues. This was the desired goal for these experiments, such that large-area, in-situ artificial duricrusts could be created in natural terrestrial landscapes for testing the mobility of prototype rover vehicles. It should

be noted that Fig. 17 and Fig. 18 show only 10 impacts for each of the Ordinary Portland Cement trials. These experiments were abbreviated based on the knowledge gained from the Martian analogue trials, where up to 20 impacts per sample was not required since the DCP will have completely penetrated the duricrust by the tenth impact.

Weak and easily penetrated duricrusts were observed for samples with low water content, independent of crust thickness. These samples possessed crumbly surfaces that failed instantly, or near-instantly during testing. It should be noted that these low-water content samples (<10% water) represent similar amounts of water observed by previous and current Mars missions [3,15,16].

Thin duricrusts with medium-to-high water content were also easily penetrated, although this was due to the crusts experiencing brittle fracture under pressure. This differs from the failure mode of the low-water content samples, but still represents a weak crust that is unable to support notable loads, such as those represented by a Mars rover like Spirit and Opportunity. Although these strongly-cemented but thin duricrusts may have been formed when the water content on Mars was higher than it is presently, they still represent a driving hazard to present and future Mars missions. Given the past observations of thin crusts on the surface [3,12,13], these represent the most-likely hazard to encounter.

Figure 18: DCP Total Depth of Penetration graph showing the 12 Ordinary Portland Cement duricrust experiments, indicating duricrust thickness and water content. The compound curves (1 - downward then upward) of the upper lines indicate the noted effect of the duricrust for these tests. Simple curves (2 - upward curve only) of the lower lines indicate that the duricrust was not well observed or that it failed early in the testing, either due to a low water content or a small crust thickness. Most of these data appear similar to tests performed with the iron oxide duricrusts, showing results that are most like the moderate crust thickness and moderate water content experiments.

Table 4: Duricrust costs (excluding silicon component)

Component	Per 100g Comp.	Per 100cc Duricrust
Fe ₂ O ₃	£2.00	£0.40
Fe ₃ O ₄	£2.40	£0.48
Al	£1.20	£0.13
MgSO ₄	£0.15	£0.03
Total Cost (Martian Duricrust)		£0.60
Cement	£0.09	£0.0037
Total Cost (Artificial Duricrust)		£0.0037

Given the performance of the laboratory-created duricrusts, many of their behaviours were qualitatively similar to terrain already encountered on Mars by current and past rover missions, notably the low-water content samples and the thin crust samples. The higher strength of the duricrust samples with higher water content and thicker crusts are less-likely to be observed on Mars, but even they did not last under repeated DCP loads and need to be treated with caution if encountered. Based on these test results and the presented data, it would be prudent to employ direct-measurement methods to ensure sufficient traversability of the terrain, such as those systems investigated during the FP7 FASTER project [7]. This project investigated several direct-measurement methods that would allow future Mars rover missions to traverse the surface with a much higher degree of confidence and certainty than has been used in the past. For field testing and large-scale laboratory testing purposes, the artificial duricrusts created with Ordinary Portland Cement proved to be a suitable physical substitute for the crusts fabricated with Martian-identified components. The low-cost nature of the cement (see Table 4) and the close performance to the Martian duricrusts make it a good alternative when only physical characteristics are being tested.

5. Conclusion

This paper has presented a means for artificially creating Mars-like duricrusts in an Earth-analogue laboratory environment. Realistic duricrust compounds based on those identified on the Martian surface were used during their creation, such as silicon, magnesium sulphate, iron oxide, and aluminium. Thirty-three samples were created using a variety of iron oxide type (magnetite – Fe₃O₄ and haematite – Fe₂O₃), duricrust thickness (ranging from 6 – 24mm), and water content (ranging from 3.62 – 42.81% by mass).

The resulting crusts were tested using a DCP, calibrated to the silicon component, an in-house soil simulant called SSC-3, which is comprised mainly of 150 - 212µm sub-angular particles of quartz (SiO₂). The laboratory-created duricrusts presented several types of behaviour, such as weak and crumbly – easily penetrated, thin and brittle – easily penetrated, and relatively strong but still susceptible to penetration. Using the DCP, the duricrust samples were classified by their density, or resistance to penetration, in numbers relative to those found in natural SSC-3 (i.e. the normal range of simulant densities, 1.42 – 1.62g/cc, without a surface duricrust).

Weak crusts and brittle crusts displayed higher relative densities than the loose soil preparations on which they rested, showing that even easily penetrated duricrusts can still be distinguished from pure, loose soil. Stronger crust samples showed their presence more so by resisting initial penetrations by the DCP. The strongest of the duricrust samples demonstrated themselves by resisting several DCP impacts before the testing device moved below the crust layer. With this last set of samples, cone penetration results very clearly showed the presence of a surface duricrust. In all of these tests, the duricrust samples were penetrated within five impacts of the DCP, indicating that although they may be relatively weak or strong, as compared to a natural soil simulant, they all represented potential hazards to traversing a terrain covered by such layers. As a result, a key finding to this study is the recommendation of direct-sensing instrumentation on future Mars rovers, to ensure suitable trafficability of the surface.

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