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Study of the formation of duricrusts on the martian surface and their effect on sampling equipment

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ABSTRACT

The Powdered Sample Dosing and Distribution System (PSDDS) of the ExoMars rover will be required to handle and contain samples of Mars regolith for long periods of time. Cementation of the regolith, caused by water and salts in the soil, results in clumpy material and a duricrust layer forming on the surface. It is therefore possible that material residing in the sampling system may cement, and could potentially hinder its operation. There has yet to be an investigation into the formation of duricrusts under simulated Martian conditions, or how this may affect the performance of sample handling mechanisms. Therefore experiments have been performed to create a duricrust and to explore the cementation of Mars analogues, before performing a series of tests on a qualification model of the PSDDS under simulated Martian conditions.

It was possible to create a consolidated crust of cemented material several millimetres deep, with the material below remaining powder-like. It was seen that due to the very low permeability of the Montmorillonite component material, diffusion of water through the material was quickly blocked, resulting in a sample with an inhomogeneous water content. Additionally, samples with a water mass content of 10% or higher would cement into a single solid piece. Finally, tests with the PSDDS revealed that samples with a water mass content of just 5% created small clumps with significant internal cohesion, blocking the sample funnels and preventing transportation of the material. These experiments have highlighted that the cementation of regolith in Martian conditions must be taken into consideration in the design of sample handling instruments.

1. Introduction

Evidence of soil induration and crusts on the Martian surface has consistently been seen in lander missions. The Viking landers were the first to observe this, with a layer of lightly cemented fine-grained sediments about 1 - 2 cm thick occurring at both landing sites. This cemented soil was designated as duricrust. Further indications of the presence of duricrusts included a large area of fractured crust mapped at the Viking Lander 2 (VL2) site and through trench operations, in which the upper layer of shovelled soil indicated a cohesive strength greater than that of the deeper, unconsolidated soil (Mutch et al., 1977). Crusty to cloddy material was also seen to occupy $\sim$ 86% of the VL2 sample field, with the cohesion seen at least partly due to cementation of the fine grains (Moore and Jakosky, 1989). The Pathfinder rover, Sojourner, also saw crusts formed at the surface of cloddy deposits, mechanically resembling those found at the VL2 site, though with smaller cohesions (Bickler et al., 1999). Both MER rovers also found evidence for the existence of such crusts. In particular, Spirit saw that soil deposits typically displayed surface crusts a few millimetres thick beneath thin dust covers, and observed surface crusts in wheel track disturbances (Arvidson et al., 2004). Opportunity's Microscopic Imager observation of disturbed soils also suggested a crust at least 1 mm thick caused by cementation of surface particles (Herkenhoff et al., 2004). Finally, the Phoenix landing site excavated a dozen trenches, and saw that the upper few centimetres of soil were crusted, and clods were seen around the trenches, with mechanical properties again similar to those of the VL2 landing site (Smith et al., 2009). From this evidence, it is likely that crusting is a near-ubiquitous phenomenon on fine materials of the Martian surface.

Currently there have been no conclusive observations concerning the chemistry of the duricrusts available, although there are a number of hypotheses as to its formation, with the cementation process likely caused by mobile salts (Hudson et al., 2007) and/or

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clay components. Evidence of clays in the Martian soil was first noted in the observations by Viking (Banin and Rishpon, 1979), and has been inferred in numerous other studies (Chevrier and Mathé, 2007). Analysis of the surface geology of the VL2 site also revealed the presence of relatively high sulphur and chlorine contents, suggesting that compounds of these elements are a significant factor in crust formation (Sharp and Malin, 1984). The soil in the Viking, Pathfinder and MER landing sites all have sulphur and chlorine contents of 4% and 1% respectively. Two models for the formation of duricrusts at the MER sites were proposed, in which transient liquid water plays a vital role in dissolving and depositing salts. Repetition of these processes over a long time period can explain the widespread distribution of the cemented soils, with the crust's thickness dependent on the length of time the transient water phase is present (Landis et al., 2004). Only a limited amount of water appears to be required, with soil crusts on the Gusev Plains likely being formed under low water activity and very limited evaporated mineral deposition (Cabrol et al., 2006).

Numerous experiments have been performed to determine the properties of duricrusts. Salt crusts created with magnesium sulphate, though with significantly more liquid water than would be present on Mars, were used to examine diffusion barriers and vapour transport (Hudson and Aharonson, 2008). Other experiments have involved examining the spectroscopic identity of sulphates on Mars and the effects of soil cementation on the soil's spectral properties (Cooper and Mustard, 2001). The effect of soil cementation on the thermal inertia of the Martian surface has also been examined (Piqueux and Christensen, 2009), and the thermal properties of the inferred Martian duricrust surfaces have been compared to the indurated surfaces on Earth (Murphy et al., 2009). Another study developed a model explaining the formation of cemented and crusted soils, investigating how the composition of these crusts affects their spectral and physical properties. It was found that material with a high smectite content resulted in a harder, thicker crust, while the palagonitic soil produced a thinner, more friable crust (Bishop et al., 2002).

Although duricrust simulants have been created and their properties studied, there appears to have been no investigation into the formation of duricrusts under simulated Martian conditions, and in particular how their properties would influence the performance of sampling and drilling mechanisms. For instance, a sample taken either from the surface or subsurface could spend several days in a sampling subsystem before being delivered to an instrument. Within this time, water present in the soil and/or the atmosphere could cause cementation of the sample, potentially to the extent at which it hinders the operation and efficiency of the mechanisms it will interact with. This could particularly happen when the material contains larger amounts of loamy analogue materials such as Montmorrillonite, which forms the main component of the ESA-defined Mars analogue materials (Durrant and Baglioni, 2013).

The *Powdered Sample Dosing and Distribution System (PSDDS)* is a part of the *Sample Preparation and Distribution System (SPDS)* of the ExoMars rover currently being developed by OHB System AG. Its dedicated task is to feed crushed Mars surface and subsurface material into other instruments for further investigation. There is a possibility that the crushed material collected by the ExoMars drill could become clumpy while lying in the instrument, which could potentially hinder the proper dosing operation of the PSDDS. In order to investigate this question experimentally, a series of tests have recently been conducted under Mars-like conditions at the *Space Research Institute/Austrian Academy of Sciences.* For these experiments a qualification model of the PSDDS, shown in Fig. 1, was used. These tests involved the creation of duricrusts using a Mars analogue material as suggested by ESA in simulated Martian conditions, and an examination of cementation of the analogue and its components. This culminated in the testing of the PSDDS, in which its sample funnels were filled with Mars analogue material and exposed to simulated Mars conditions.

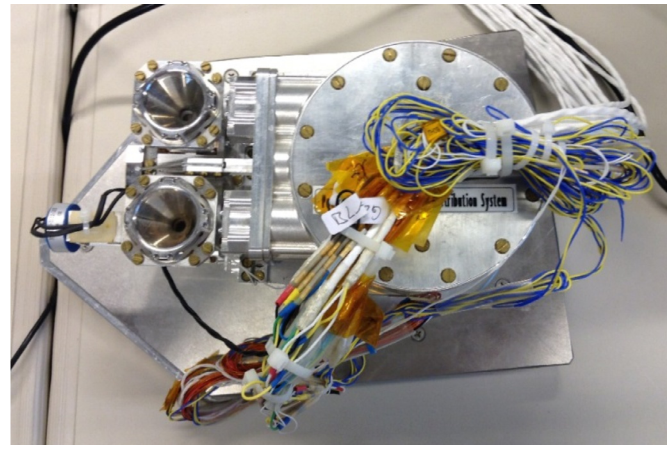

Fig. 1. PSDDS breadboard model as configured for the sample cementation tests.

Table 1
Composition of the S7 regolith simulant (Durrant and Baglioni, 2013).

Simulant Component	Quantity
Montmorillonite	67%
Magnesium sulphate heptahydrate (Epsom salt)	30%
Magnesium perchlorate hexahydrate	3%

The outline of this paper is at follows. In Section 2, an initial series of experiments is described in which water vapour is introduced to a sample of the analogue material at Mars atmospheric conditions, before undergoing a cooling and heating cycle. The formation of the duricrust over time is then presented. Section 3 examines the degree of permeability and subsequent cementation of the materials that make up the analogue. Section 4 describes the experiments performed with the PSDDS, with the aim of determining if cementation of the sample affects the dosing mechanism. Finally, Section 5 contains our conclusions and recommendations.

2. Creation of duricrust in a simulated martian environment

The first aim of the experiments performed was to verify if the surface of Mars can be chemically cemented under conditions that are similar to the Martian environment. The material used for these experiments is the S7 analogue, an unconsolidated clay/salt regolith simulant verified for use in the validation and testing of the Drill and SPDS mechanisms of the ExoMars rover, with its composition given in Table 1.

2.1. Experimental Set-up

These tests involved a sample of the S7 simulant, held in a cylindrical container of 7 cm diameter and 3 cm height. In order to simulate the Martian environment, a number of conditions must be met. To account for the presence of water in the soil, the sample is wetted by directing the flow generated by a water disperser producing very fine water droplets (micrometre-size range) in a tube towards the initially dry sample surface. The sample is placed in a vacuum chamber of 40 cm diameter and 40 cm height. To simulate the Martian atmosphere, a high precision pressure regulation valve and vacuum pump are used to establish a stable Mars surface pressure of 6 – 8 mbar, and CO_2 can be fed into the chamber via an inlet. The final part of the test is to simulate the cycles of heating and cooling that would be experienced on Mars.