Soil simulant sourcing for the ExoMars rover testbed

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Abstract

ExoMars is the European Space Agency (ESA) mission to Mars planned for launch in 2018, focusing on exobiology with the primary objective of searching for any traces of extant or extinct carbon-based micro-organisms. The on-surface mission is performed by a near-autonomous mobile robotic vehicle (also referred to as the rover) with a mission design life of 180 sols (Patel et al. (2010)). In order to obtain useful data on the tractive performance of the ExoMars rover before flight, it is necessary to perform mobility tests on representative soil simulant materials producing a Martian terrain analogue under terrestrial laboratory conditions. Three individual types of regolith shown to be found extensively on the Martian surface were identified for replication using commercially available terrestrial materials, sourced from UK sites in order to ensure easy supply and reduce lead times for delivery. These materials (also referred to as the Engineering Soil (ES-x) simulants)

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are: a fine dust analogue (ES-1); a fine aeolian sand analogue (ES-2); and a coarse sand analogue (ES-3). Following a detailed analysis, three fine sand regolith types were identified from commercially available products. Each material was used in its off-the-shelf state, except for ES-2, where further processing methods were used to reduce the particle size range. These materials were tested to determine their physical characteristics, including the particle size distribution, particle density, particle shape (including angularity / sphericity) and moisture content. The results are analysed to allow comparative analysis with existing soil simulants and the published results regarding in-situ analysis of Martian soil on previous NASA (National Aeronautics and Space Administration) missions. The findings have shown that in some cases material properties vary significantly from the specifications provided by material suppliers. This has confirmed the need for laboratory testing to determine the actual parameters to prove that standard geotechnical processes are indeed suitable. The outcomes have allowed the confirmation of each simulant material as suitable for replicating their respective regolith types.

Keywords: Mars, rover, ExoMars, terrain, regolith, soil, simulant, characterisation

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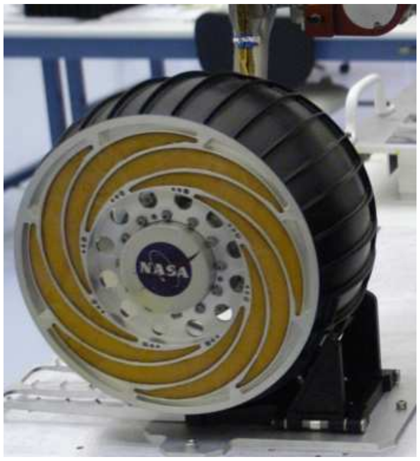
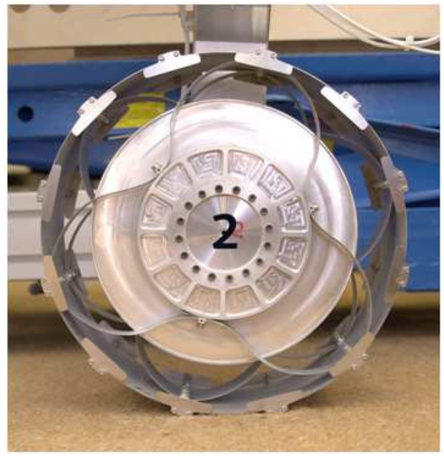
1. Introduction

. The development of the mobility system of the ExoMars rover has been an extensive process of iterative analysis and testing. The baseline configuration is now confirmed as a 3-bogie suspension system, mechanically simpler than the dual rocker-bogie systems used on NASA (National Aeronautics and Space Administration) Martian rovers while remaining equally capable on difficult terrain (Patel et al. (2009)). ExoMars will pioneer a unique new flexible wheel, designed to improve traction through increased contact area over an equivalent rigid wheel (Patel et al. (2010)). Wheel concepts from both ExoMars and the Mars Exploration Rovers (MERs) are shown in Fig. 1. Much of the assessment of these systems has relied heavily on analytical modelling of the mechanical performance of the chassis during traverses across typical Mars-type terrains, replicating the slopes and rock distributions observed on previous Mars missions. Some experimental work has provided empirical data supporting these results, and the flexible wheel development has also included traction testing across loose, sandy terrain similar to the regolith found on the Martian slopes (sand dunes). The final validation stage for the mobility system will rely on the combination of these methods, and require a thorough testing of a full, terrestrial prototype of the rover on laboratory terrain analogues. This will include the use of Engineering Soil (ES) simulants that have been selected due to their mechanical similarities to those the ExoMars rover is likely to encounter when traversing the Martian regolith.

. The use of regolith simulants in terrestrial laboratories is common practice (Oravec et al. (2010)). These materials allow for terrains extremely similar to those found on planetary surfaces to be prepared. Thanks to the numerous lander and rover missions sent to explore the Martian surface, some data are available on the material composition of soil at various sites across the planet. Two of the earliest Martian missions, the Viking I and II landers, searched for evidence of life and water with a robotic scoop, used to scrape



(a) MER wheel (Diameter approx. 26cm). (Courtesy NASA/JPL-Caltech)



(b) ExoMars flexible wheel (Diameter approx. 25cm). (Courtesy Patel et al. (2010)).

Figure 1: Examples of planetary rover wheels.

away at the top few centimetres of the regolith surrounding the landing sites. In the 1990s the Pathfinder lander touched down on Mars carrying the Sojourner microrover, subsequently proving traversal of the Martian regolith as possible. Sojourner also carried the Wheel Abrasion Experiment (WAE) and used it successfully to profile the abrasiveness of the regolith particulates, in turn providing insight into the particle shapes. The two MER missions following Pathfinder carried the first optical microscopes to Mars, in addition to several spectrometers, and thanks to the unprecedented success of these rovers we now have regolith composition data from a huge range of sites across many kilometres (Herkenhoff et al. (2008)). The latest lander mission to Mars, Phoenix, extended the findings from the Viking missions. The primary experiment carried on the lander, the Thermal and Evolved

Gas Analyser (TEGA), further profiled the compounds found in the regolith and the trenches left by the scoop action provided some indication of the mechanical behaviour to terrain analysts (Bonitz et al. (2008)).

. The challenge for engineers is to ensure the terrestrial materials used in these cases are similar in their physical and mechanical parameters to those observed on the Martian surface. Common mechanical parameters, such as the internal friction angle and cohesion, are often used as a specification. However, other physical parameters, including particle size distribution (PSD), dry bulk density and particle shape (including grain angularity/sphericity), must also be considered. For the purpose of traction testing, the chemical composition of prospective simulant materials is not normally necessary for consideration during the selection process (Seiferlin et al. (2008)). The study of the mechanical parameters of Engineering Soil Simulants will be discussed in detail in a future publication. Three material types were identified for use in ExoMars traction testing:

- Engineering Soil Simulant-1 (ES-1): a fine dust analogue
- Engineering Soil Simulant-2 (ES-2): a fine aeolian sand analogue
- Engineering Soil Simulant-3 (ES-3): a coarse sand analogue

. These materials represent respectively the material comprising the fine covering found across the Martian surface, the aeolian materials commonly found in larger accumulations such as dunes, and coarser materials also found on these slopes. Fig. 2 provides an image indicating the MER Spirit in an attempt to traverse similar materials on the Martian surface. This terrain type has resulted in the rover becoming trapped in the loose regolith. A more thorough review of these Martian sand types is provided in Golombek et al. (2008).

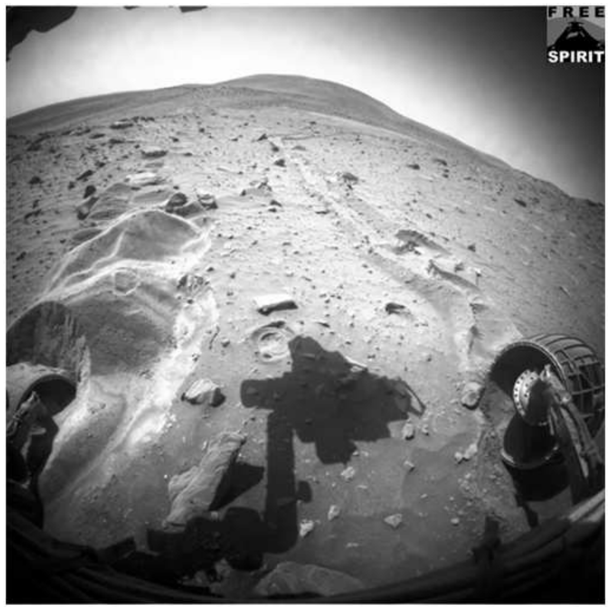


Figure 2: Loose regolith on the Martian terrain (Courtesy NASA/JPL-Caltech).

. This paper will detail the processes and reasoning used in the selection of suitable materials for these simulants. Firstly the physical and mechanical parameters used in the selection will be defined, and a brief summary of other simulants currently in use will be presented. The options considered for the simulants are discussed and reasoning is provided for the materials selected. The test methodology used to analyse each of the selected materials will be explained and results presented. Finally the measured parameters are compared with the required specification and the specification reference data provided by the suppliers.

2. Defining simulant properties

. Analysis of the Martian terrain and topography has formed a major part of almost every orbiter, lander and rover mission to the planet. Characterisation of the composition of the Martian surface is crucial for future mission development, whether in determining the functionality of new instruments and experiments or, more practically, in the design of lander, rover or drill hardware for use on the extreme conditions presented by the terrain types.

2.1. Simulant parameters

. The parameters used to define a simulant are the same as those used in the study of the physical and mechanical properties of granular soils for geotechnical purposes. These are both quantitative and qualitative in nature, providing a complete description of the physical and mechanical properties from the individual particle to the soil mass. It is these parameters which are used in the modelling of soil strength and prediction of trafficability for vehicle applications. It is also understood that in many cases these parameters are highly empirical. Testing is carried out on selected samples of the chosen simulant material; however, it is rare to find loose materials in wide-spread homogenous regions. Subtle differences in the grading mix, moisture content and shape can significantly alter measured properties. As such it is normally necessary to take multiple measurements and provide either an average value or parameter range for a specific terrain region.

. The three material types identified for this investigation are classified primarily by their PSD. Additional physical properties also identified in the classification process include particle density and particle shape. Measuring particle density allows for the determination of the void ratio of each simulant when prepared at different bulk densities by various preparation methods (Gouache et al. (2010)). The testing of the mechanical parameters (reported in a future publication) require the density of each sample to be varied. To provide a value of the relative density, maximum and minimum density measurements are required. Particle shape provides evidence useful in the analysis of the shear strength properties of each material.

2.2. Martian terrain types

. Mars is a dry planet with surface temperatures well below the freezing point of water. There are no known major bodies of surface water, leaving the terrain barren and similar to hot deserts on Earth. Conditions are analogous to several locations on the Earth's surface; the dryness and deep, loose sand of the hot deserts, rocky outcrops and plateaus of volcanic lava rock fields. Indeed, many topographical and terrain analogues can also be found in numerous regions in Australia, including rocky plains similar to those observed by the Viking 1 lander (West et al. (2010)), and the similarities of many regions of Argentina to the Martian surface are discussed in Pacifici (2009). These include large scale formations, such as tabular lava flows and meteorite impact-like craters, to much more localised examples, including rocky till deposits in smaller sloped regions similar to that shown in Fig. 3.

Figure 3: Terrestrial and Martian scree slopes, Pacifici (2009).

. On a far smaller scale, the discussion in Golombek et al. (2008) identifies numerous soil types on the Martian surface, including aeolian deposits, based on Viking, Pathfinder/Sojourner and MER data. These include drift deposits, having low friction angles in the region of 15-21 degrees and low bulk densities of 1000-1300 kg$\cdot$m^{-3}. These are likely to be atmospheric dust particles, 2-4 μm in diameter, yet found in deposits thick enough to envelope an entire footpad of Viking 1, a sinkage of 16.5 cm. The terrain surroundings of the MER rovers have also been analysed using the Miniature Thermal Emission Spectrometer (Mini-TES) and Microscope Imager (MI) instruments on both Spirit and Opportunity. Measurements of fine grained dust have indicated particle sizes of up to 45 μm. When observing less fine sand deposits comprising the dunes and bedforms, Opportunity has found them to be relatively dust free, with particle sizes of approximately 130-160 μm. Spirit has also observed similar sand bedforms with particle sizes of approximately 60-160 μm.

. These measurements made by the various Martian surface missions can be used to select (or create) terrestrial materials analogous in their behaviour, dependent on the required application. In the case of materials replicating the trafficability properties of particular terrain, a broad and mature set of geotechnical test methods and standards can be used to ensure appropriate materials are selected. The materials in question will need to be close in mechanical nature to those anticipated at a particular mission site. Factors such as the chemical composition need not be considered in these cases. Furthermore the terms “soil”, “regolith” and “simulant” are used interchangeably throughout this paper. Although strictly speaking the term “soil” can in some cases imply the presence of biological processes in its development (Seiferlin et al. (2008)), it should not be assumed that this is the case here. Additionally, "regolith" is commonly used to describe loose materials comprising of a broad range of particle grain sizes and larger objects such as gravel, rocks and boulders (Heiken et al. (1991)). The materials used here are all assumed to be homogenous in their PSD.

2.3. Simulants in use today

. The source material used in the manufacture of a simulant is dependent on the desired application of the final product. Other than physical and mechanical simulation, analogues may be selected to replicate properties including the chemical, magnetic, thermal or organic behaviour (Marlow et al. (2008)). Mechanical soil simulants for Martian testing have been primarily sourced by NASA JPL from two locations, the Hawaiian volcanic regions and the Mojave Desert. The weathered ash deposits of Hawaiian volcanoes were used to manufacture the simulant JSC Mars-1 throughout the 1990s. However, in more recent years the Pathfinder, MER and Phoenix missions have provided data on a broad range of areas from widespread Martian surface locations (Peters et al. (2008)). These data informed the development of a subsequent simulant with mechanical parameters closer to those measurements, the Mojave Mars Simulant (MMS). Other simulants are in use in the various laboratories situated at JPL. These include crushed volcanic rock, used in the MER yard; a decomposed granite and brick dust mixture, used in the more general purpose Mars Yard; a dust free and washed silica sand in the JPL Lab 107; finally a dust free garnet mix is used in JPL Lab 82 (Perko et al. (2006)). ExoMars rover traction testing, until recently, has been performed on various dust-free washed and dry quartz sand in the Astrium Mars Yard (Patel et al. (2009)). Martian soil simulants in use at the Surrey Space Centre are also produced from similar source materials. SSC-1 is a coarse, dusty silica sand and SSC-2 a crushed garnet powder (Brunskill and Lappas (2009); Scott and Saaj (2009)).

. It is seen that material simulants can be sourced widely from carefully selected sites across the Earth's surface. The data provided by the Viking, Pathfinder, MER and Phoenix missions have extensively characterised and classified the most broadly encountered regolith types. These results provide all the information necessary to select new materials from local sources for specific terrain simulation requirements, regardless of the geographic location of the laboratory.

3. Material selection

. The materials considered below are all commercially available products, procurable "off-the-shelf" in large bulk quantities. The final products selected for the new simulants were initially purchased in smaller quantities of 3 tonnes. The outcome of the testing regime discussed below was intended to confirm the physical and mechanical parameters of these materials were within the required specification. On completion of a successful test campaign, the specification called for the selected materials to be available in bulk quantities in excess of 70 tonnes within a period of few days. This ruled out the option of sourcing the simulants from new, raw materials in order to reduce both the time required for production and the final cost of procurement.

3.1. Required specification

. In the Astrium-led study which identified the common Martian regolith types discussed in Section 1, the proposed simulants would be differentiated by their PSD. In addition, it was requested that ideally the materials were to be comprised of silica sand, in the cases of ES-2 and ES-3, and Nepheline powder in the case of ES-1, where an extremely fine material was required. Finally, the ideal particle shapes were identified, but not specified as mandatory to the requirements. The specifics of these requirements are summarised in Table 1.

. The PSD of numerous silica sand products from a range of UK-based aggregate suppliers were analysed and compared in an effort to identify those best matching the simulant requirements. Three materials providing a close match to the PSD requirements in Table 1 were identified, using the data-sheet PSD data. The data-sheet parameters for each of the proposed materials are summarised in Table 2. Their gradings are plotted with the particle size requirements overlaid in Fig. 4. All three materials are supplied by Sibelco UK Ltd and each option is a standard off-the-shelf material. Stjernoy Nepheline Syenite powder is available in a number of gradings, however the S7 variant best fit the required modal particle size. Leighton Buzzard DA30 was found to be an ideal fit for the ES-3 requirement. Red Hill 110 was the best fit available for ES-2, however the PSD data provided by the supplier indicated only approximately 40% by weight would be within the specification. The issue of the off-set PSD would be solved through further processing of the off-the-shelf material to bring it in line with the specified range. The particle shapes were not ideal in all cases but still suitable for this use.

Table 1: Summary of requirements for the three regolith simulants. Prime requirements are considered to be the PSD and the nature of the particles.

	ES-1	ES-2	ES-3
Maximum size (μm)	32	125	20,000
Minimum size (μm)	<10	>30	>30
Modal size (μm)	10	-	400-600
Nature	Nepheline	Quartz	Quartz
Shape	-	Sub-rounded	Angular to sub-angular

Table 2: Candidate material parameters as specified in the respective data sheets.

Simulant	ES-1	ES-2	E
Proposed material	Stjernoy Nepheline Syenite S7	Red Hill 110 silica sand	Leighton Buzza
Maximum size (μm)	30	250	
Minimum size (μm)	<3	60	
Shape	Angular	Subrounded	Ro

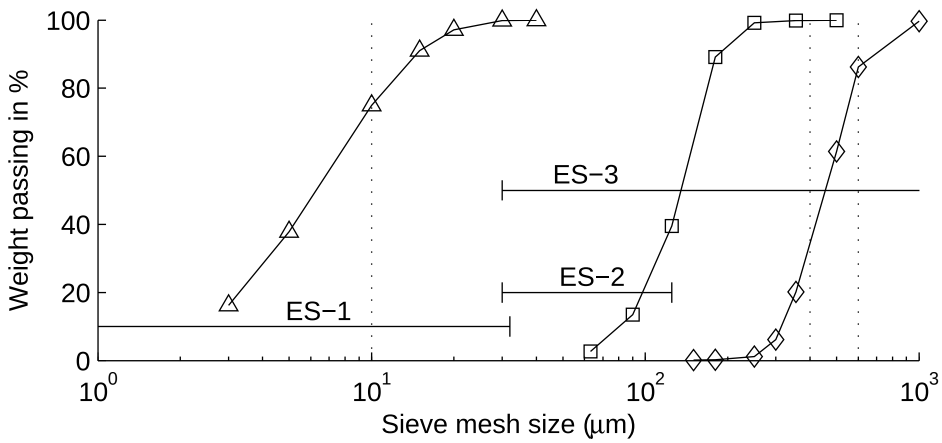


Figure 4: Materials initially proposed for use. The horizontal black lines show the particle size range requirements and the vertical dotted lines the modal particle size targets. The upper size requirement for ES-3 and the lower one for ES-1 are off scale (see Table 1 for details). The different materials are represented by: triangles (Stejorny 7), squares (Red Hill 110) and diamonds (Leighton Buzard).

3.2. Post-processing silica sand materials

. Two different post-processing methods were used in an attempt to remove the oversize material from the Red Hill 110 sand, industrial scale sieving and milling. Large wire mesh sieves are fed with the desired material and vibrated to agitate the particles down the length of the sieve. As the material passes over the sieve particles fitting or below the mesh grade are removed and collected, leaving the excess to accumulate at the end of the process. This method is moderately fast, but does require extensive set up of the machinery, which may add several days to the overall processing time. With respect to this, it is normal for bulk quantities to be measured in tens of tonnes, to improve the overall efficiency of a processing run.

. The alternative approach made use of a milling process to reduce the larger particles to sizes within the required specification, rather than removing them outright. Material is ground between two plates for a time proportional to the average needed in breaking down the portion of larger particles. An air classification system is then used to remove any excess in the fines produced in this method. The processing quantities and equipment reset times were similar to those of the sieving method. In both cases a relatively small quantity of 3 tonnes of Red Hill 110 was provided, used as a test sample to assess the effectiveness of the machinery in achieving an output close to the ES-2 specification. The quantity was determined by the requirement of 1 tonne of ES-2 to complete the mechanical testing from the expected best case yield (using the sieving process) of 40%.

. Despite promising initial results in tests of small samples of Red Hill 110 using hand sieves, the bulk sieving equipment struggled to maintain high yields of output material, typically 10% or worse. Further investigation showed the vibration method used did not prevent the sieves from becoming excessively clogged, or pegged, by larger particles. A sample was tested using a mechanical laboratory vibration platform at the University of Surrey and verified the problem. Fig. 5(a) shows the datasheet grading data of Red Hill 110. It also shows the PSD plots for a single sample of Red Hill 110 run through the mechanical vibration platform multiple times; the contents of the sieves left untouched with each run, except for the 150 μm contents which were passed back through the stack. This confirmed the pegging issue identified by the processing company. It was suggested the most likely cause for the unexpectedly high levels of pegging was due to the original target size of the particles. In the case of Red Hill 110 it is likely this was close to or at the 125 μm upper limit set in the ES-2 specification. The action of crushing and milling larger gravel and rock pieces produces a wide range of particle sizes; however, the process aims for a target modal particle size. This is likely to have been equal or close to the targeted upper limit of 125 μm and resulted in the high pegging rate encountered during processing. This outcome resulted in the investigation of alternative processing methods.

. Further milling of the material would remove the larger particles through a crushing process. Two tonnes of Red Hill 110 was subjected to the milling process and the resulting material was found to be free from oversize particles. However, the particle strength was found to be much lower than that of similar materials. A yield of approximately 50% was estimated from this process. However, on examination of the milled Red Hill 110 approximately 75% fell outside of the lower particle size boundary. A PSD plot is shown in Fig. 5(b). Even when air classified, the remaining material would retain a high bias in PSD toward the much finer material and the overall yield from the entire process would still fall slightly below the quantity required for mechanical parameter testing. Furthermore, the process of milling tends to produce highly angular particles, where aeolian sands are typically well rounded. This would not meet the requirements for the desired ES-2 material.

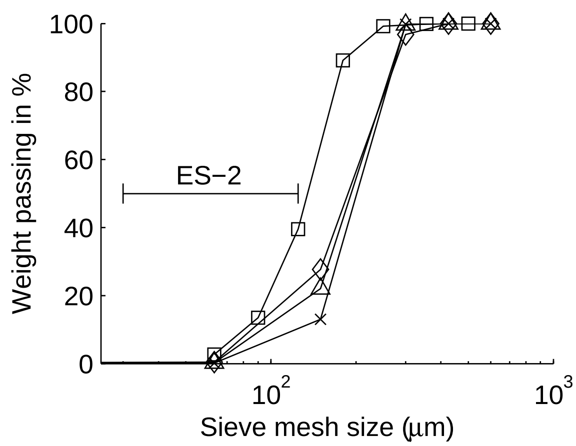
3.3. Final simulant materials

. The material selected and procured for ES-1 was a dry Nepheline powder. From the various options available from the supplier Stjernoy 7 was selected as the final material for use as the simulant. Due to the problematic nature of the procurement and post-processing of a material for use as ES-2, no material was obtained in the large quantities needed to complete all mechanical testing. After an exhaustive search, off-the-shelf soils either fell outside of the PSD requirements or were based on non-quartz mineral sands; neither of which were desired properties. The additional processing of Red Hill 110 proved unsuccessful in the attempts at manufacturing a suitable simulant in large quantities. In total, approximately 25 kg was produced as part of the sieving process out of the procured 3 tonnes and it is this material which is used as ES-2 in the following tests. The quartz-based Leighton Buzzard DA 30 sand, also available off-the-shelf from Sibelco, was selected for ES-3.

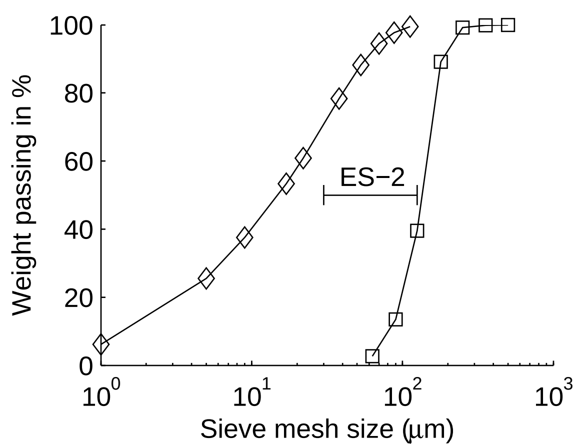
4. Simulant physical properties

4.1. Density

. The particle density is measured using a graduated cylinder containing a known volume of water (by mass), based on the standard method in ASTM



(a) The data is represented by: squares (Red hill 110 datasheet), crosses (Red hill 110 run 1), triangles (run 2) and diamonds (run 3).



(b) The data is represented by: squares (Red hill 110 datasheet) and diamonds (milled Red hill 110).

Figure 5: (a) Variation in Red Hill 110 PSD with multiple sieving runs. (b) Comparison of PSD of milled Red Hill 110 and original Red Hill 110. The horizontal black lines show the particle size range requirements for ES-2.

(2010). A known mass of dry simulant is added to the cylinder in a quantity small enough to allow the complete submersion of the sample. The change in total volume is measured and the volume of water subtracted. The resulting volume is that of the sample and is used with the mass to calculate the particle density. The results are presented in Table 3.

Table 3: Simulant particle densities (kg·m^{-3}).

Simulant	Measured (kg·m^{-3}) (standard deviation)	Common values observed (kg·m^{-3})
ES-1	2320 (45)	2550-2650 (Nepheline)
ES-2	2560 (65)	2600-2700 (Quartz)
ES-3	2600 (45)	

4.2. Particle shape

. An ideal simulant would match both the PSD and shape parameters identified in the specification. However, this laid too tight a constraint on the available materials to fulfil both parameters. For example, the crushing and milling used to obtain the targeted PSD for ES-2 generated angular to subangular particle shapes where subrounded particles were preferred. As such, particle shape was considered secondary to an appropriate PSD in the selection of the materials used for each simulant. It is, however, still of interest to note the resultant particle shapes for future reference.

. Each simulant was observed under a microscope at magnifications of up to 10x. The resulting images were captured with a digital camera and are shown in Fig. 6. Bulk samples are also shown in this figure. A summary of the resultant particle shapes is given in Table 4.

Table 4: Simulant particle shape analysis.

Simulant	Shape (observed)	Shape (specification)
ES-1	Angular	Angular
ES-2	Angular to subangular	Subrounded
ES-3	Subrounded to rounded	Rounded

4.3. Particle size distribution

. The PSD for each simulant was verified in the laboratory using samples of the final material. For these tests two methods were utilised:

Method 1:. For the higher graded simulants (ES-2 and ES-3) the ASTM D422-63(2002) (ASTM (2002)) standard was followed. As this standard is designed for particles of size greater than 75 μm, a minor modification to the standard was made by the addition of smaller mesh sieves, to determine the finer particle quantities. The sieving technique determines the percent weight passing a series of stacked sieves mounted to an Endecott type sieve shaker platform, providing lateral and longitudinal motion. Sieves were available at the following increments (all in μm): 53, 63, 75, 90, 106, 125, 150, 212, 300, 425, 600, 850, and 1180.

Method 2:. For the very fine simulant material used for ES-1 the ASTM standards do not apply. Therefore, an alternative method was employed, the Coulter Counter test. The fine particulate material is allowed to flow

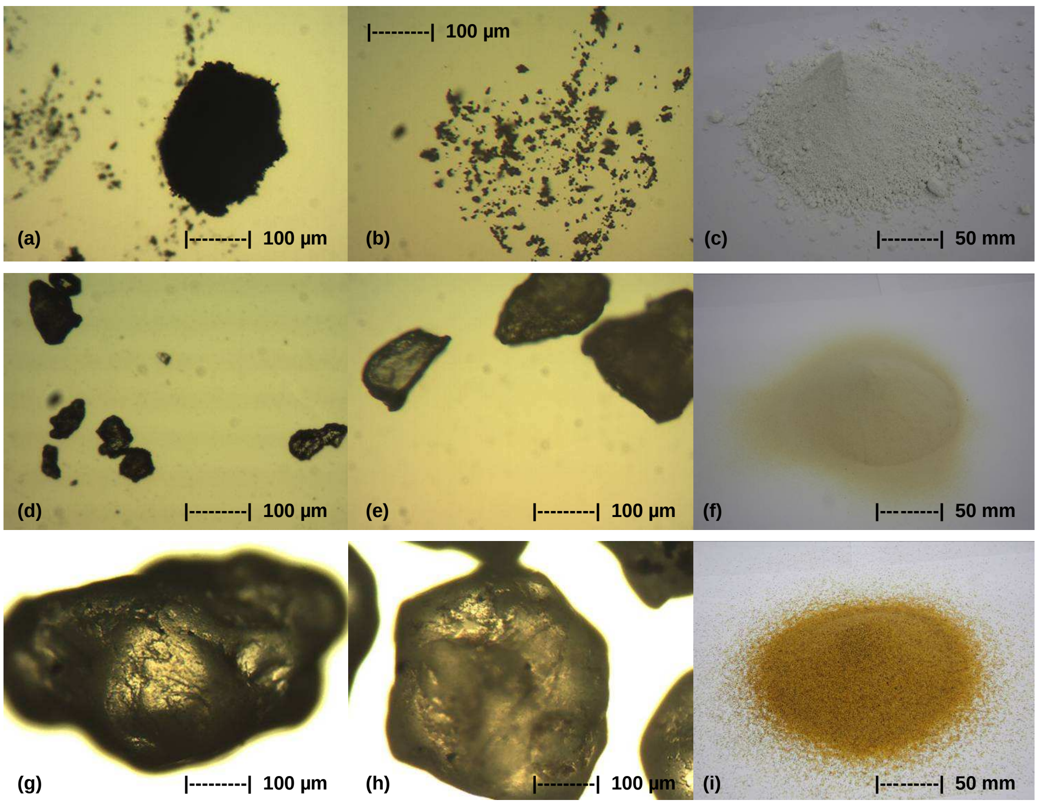


Figure 6: Microscope images of ES-1 (a, b), ES-2 (d, e) and ES-3 (g, h) and bulk samples of ES-1 (c), ES-2 (f) and ES-3 (i).

through a fluid and an electrical charge is passed through the particles to determine the size of the particles as they pass. This is used to determine the PSD to sub-micron accuracy.

. Each simulant PSD was measured using the above methods to verify the data provided in the specification sheet. The PSD plots for all three simulants are shown in Fig. 7.

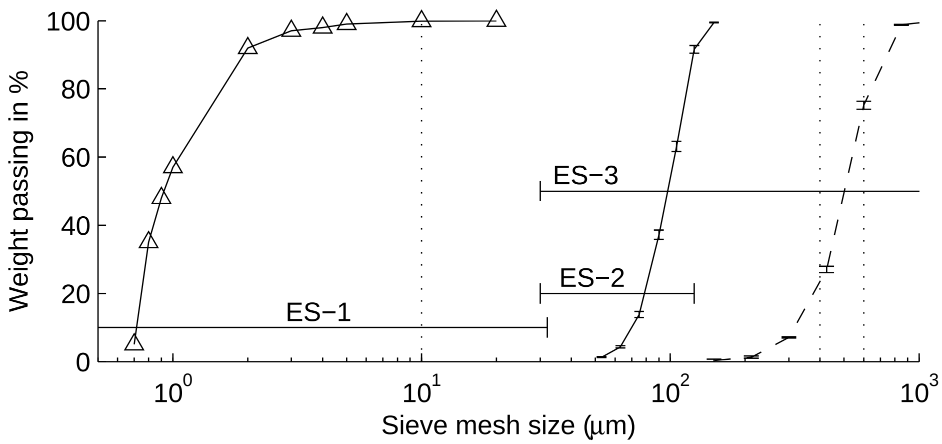


Figure 7: Particle size distribution plots for ES-1, ES-2 and ES-3 obtained experimentally. The data is represented by: triangles (ES-1), dashed line with error bars (ES-2) and full line with error bars (ES-3). The horizontal black lines show the particle size range requirements and the vertical dotted lines the modal particle size targets. The upper size requirement for ES-3 and the lower one for ES-1 are off scale (see Table 1 for details).

ES-1. The requirements for ES-1 stated that the upper range of the PSD be no greater than 32 μm and that the sample should also contain particles that are smaller than 10 μm. The particles are, in general, slightly smaller than the technical specifications state. However, they remain within the specification requirements.

ES-2. A sample of Red Hill 110 was acquired for PSD testing to confirm the range specified in the data sheet, as discussed in Section 3.2. The PSD plots shown in Fig. 5 are based on sieving tests run in the laboratory on Red Hill 110 and the grading data provided by the milling company after the alternative method was attempted. The data in Fig. 7 shows that the sieving process was ultimately effective at removing the upper portion of grades; however, the yield was severely limited by the sieve pegging issues.

ES-3. There were no difficulties in procuring this material. The material being the ideal case of a silica based sand and available directly off-the-shelf with no additional processing required; it was accepted as the material for simulant ES-3 after confirming the PSD was appropriate. A small sample of the material was also subjected to the ASTM standard test method.

4.4. Moisture content

. Latent moisture is present in both the laboratory atmosphere and as a part of the simulant material. Atmospheric moisture was measured daily during the testing using a humidity monitor and maintained with the building climate control system and a dehumidifier, where necessary. Tests were carried out in "dry conditions", where the ambient humidity levels were measured regularly and recorded at levels no lower than 25% and no greater than 40% in the case of the results presented here.

. The moisture content of each simulant was measured using a sample of the material used in each of the conducted tests. The method used followed the

ASTM D2216-05 standard (ASTM (2005)). To manage the moisture content variation through the duration of the testing regime, the soils were secured in air tight steel drums and stored in a dry laboratory space. Three samples of each of the three soils were collected under normal conditions, weighed, and dried in an oven at 110 ^{o}C for 48 hrs (after which no more mass variation was observed). The difference in mass was recorded to determine the moisture content as a percentage. The results are averaged to determine the overall moisture content of each simulant, shown in Table 5. Each simulant has a moisture content of significantly less than one percent. For the purposes of a Martian regolith simulant this is considered dry enough to provide an appropriate analogue of the mechanical behaviour.

Table 5: Moisture content of each simulant from test samples.

Simulant	Average (standard deviation) in %
ES-1	0.35 (0.03)
ES-2	0.19 (0.03)
ES-3	0.34 (0.05)

5. Discussion

. The question of what makes a suitable regolith analogue would appear to be strongly influenced by the application intended for its use and the interpretation of data available in the quantification of the material properties. For the purpose of the study described here, three Martian soil simulants were selected based on the identification of distinct examples of drift sands. These loose, dry regions of a planetary surface present one of the most challenging terrains over which an autonomous rover is required to traverse. Variations in the surface compaction and structure can vary widely, instantly and unexpectedly. To understand the surface trafficability when considering the terramechanics of such robotic exploration vehicles, it is necessary to fully understand the parameters which describe the soil mechanics of the terrain in question.

. The described simulants for the testing of the ExoMars rover mobility performance were selected based on the PSD. The ability in two of the three cases to procure materials off-the-shelf presented a quick, low-cost method to produce terrain analogues for vehicle testing. This approach provides considerable time, cost and human resource savings compared to those identified in other, similar simulants when manufacturing the material from a raw source, such as a rock bed. Moreover, the attempts to use post-processing methods produced unpredictable and time consuming setbacks, specifically when starting with a material already subjected to some level of processing.

. With this in mind, the test regime adopted for each of the materials selected for their respective simulants resulted in a comprehensive set of fundamental particle property data. These will form the basis of all further mechanical behaviour analysis during the testing schedule both on the mechanical behaviour and the response to supporting a 300 kg exploration rover like ExoMars. It is worth noting at this stage that further experimentation with the Nepheline used for ES-1 will be performed to further characterise this interesting material. In these tests it has been treated as a granular material, as is the case with ES-2 and ES-3. However, further insight may be gained into the behaviour from the perspective of a powder material. This will be addressed in future experiments, which will also include a study of the particle shape and features at a greater magnification than that provided by the optical microscope.

. A final observation on the selection of these materials is the variation in the published PSDs and those measured in laboratory tests. Fig. 8 combines the plots in Fig. 4 and 7. The data provided for Leighton Buzzard DA 30 closely matches the specification, however the similar but less coarse Red Hill 110, as discussed above, presented difficulties in sieving it to the ES-2 specification. The cause for this is assumed to be related to the sieve mesh size used. The lack of difficulty with the Leighton Buzzard sand would appear to indicate that a prudent choice in sieve sizes may help avoid issues such as these in future attempts using similar methods.

. The Nepheline powder also appears to differ significantly in its PSD when compared to the published data. Many different methods exist to measure the PSD. In general these data are inferred from indirect measurements and the results are only as good as the correlation relationship used in specifying the PSD. The Coulter Counter method used to measure the Nepheline PSD provided a better distribution based on the requirements of the experiments discussed in this paper.

. The experimental dispersion obtained on each of the selected and studied simulants is quite low. The maximum standard deviation obtained was 1.5% of passing weight (for ES-2). However, if very large quantities of a given material are procured to fill a large rover test bench for instance, it is expected

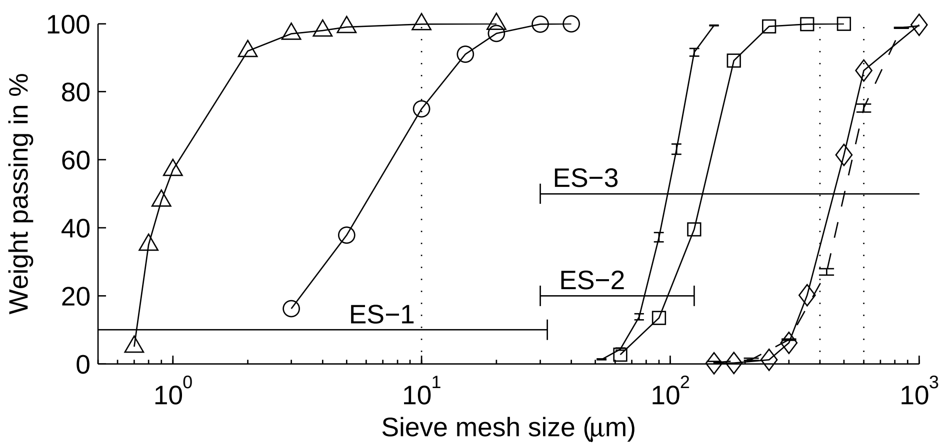


Figure 8: Particle size distribution comparison between datasheet values and measured values. The data is represented by: triangles (ES-1), full line with error bars (ES-2), dashed line with error bars (ES-3), circles (Nepheline), squares (Red Hill 110) and diamonds (Leighton Buzzard DA 30). The horizontal black lines show the particle size range requirements and the vertical dotted lines the modal particle size targets. The upper size requirement for ES-3 and the lower one for ES-2 are off scale (see Table 1 for details).

that much more deviation may be observed. Indeed, if the source of the material and its processing are not subject to very strict and costly quality control there will be variations from one batch to another. It is key to measure the fundamental properties of each delivered batch to quantify the dispersion in PSD.

6. Conclusions

. The selection of appropriate materials for use as soil simulants requires extensive work in source identification and validation of specification datasheet. While the range of options in general is considerably broad, the restriction to specific particle size ranges limited the choice of suitable materials. Subranges of particle sizes have been identified within off-the-shelf materials in the post-processing methods used on Red Hill 110, most likely due to standards in target particle cut sizes when the source rock is ground at the processing stage. However, both ES-1 and ES-3 materials were found off-the-shelf with a fit within the accepted particle size ranges. No problems were encountered during procurement, delivery or during the parameter validation.

. The tests performed on ES-1, ES-2 and ES-3 in the laboratory followed methods used widely in geotechnical engineering. The small sample of ES-2 matched the required distribution after processing, but was not available in large quantities. The Leighton Buzzard DA 30 used for ES-3 was the only off-the-shelf material to match its specification sheet. The Martian regolith simulants were selected primarily on their PSDs and modal particle size. However, with datasheets providing only guideline specifications and further problems highlighted when trying to validate the data using laboratory equipment (particularly when sieving), it has proved to be a particularly difficult parameter to work with.

. Future simulant specifications may benefit by the definition of a broader PSD range and focus instead on ensuring suitable particle shapes. This also raises the underlying issue with the angular nature of the ES-2 simulant, as aeolian materials are commonly found to comprise of more rounded particles.

. From the perspective of mobility testing the materials selected for ES-1, ES-2 and ES-3 are considered suitable for use as simulants in the testing of the ExoMars rover. Although it is unlikely the Red Hill 110 on which ES-2 is based will be used extensively, due to the issues with bulk procurement, the wide availability and off-the-shelf suitability of Leighton Buzzard 30 (ES-3) and Nepheline Syenite S7 (ES-1) showed them to be ideal matches for the analogue requirements.

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8. References

ASTM, 2002. Standard test method for particle-size analysis of soils.

ASTM, 2005. Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass.

ASTM, 2010. Standard test methods for specific gravity of soil solids by water pycnometer.

Bonitz, R., Shiraishi, L., Robinson, M., Arvidson, R., Chu, P., Wilson, J., Davis, K., Paulsen, G., Kusack, A., Archer, D., et al., 2008. NASA Mars 2007 Phoenix Lander Robotic Arm and Icy Soil Acquisition Device. J. Geophys. Res 113, –.

Brunskill, C., Lappas, V., 2009. The effect of relative soil density on micro-rover trafficability under low ground pressure conditions, in: Proceedings of the 2009 International Society for Terrain and Vehicle Systems (ISTVS) European Conference.

Golombek, M.P., Haldemann, A.F.C., Simpson, R.A., Fergason, R.L., Putzig, N.E., Arvidson, R.E., III, J.F.B., Mellon, M.T., 2008. Martian surface properties from joint analysis of orbital, Earth-based and surface observations. Cambridge University Press. chapter 21. pp. 468–497.

Gouache, T., Brunskill, C., Scott, G., Gourinat, Y., Coste, P., Gao, Y., 2010. Regolith simulant preparation methods for hardware testing. Planetary and Space Science .

Heiken, G., Vaniman, D., French, B., 1991. Lunar sourcebook: A user's guide to the Moon. Cambridge Univ Pr.

Herkenhoff, K.E., Golombek, M.P., Guinness, E.A., Johnson, J.B., Kusack, A., Richter, L., Sullivan, R.J., Gorevan, S., 2008. In situ observations of the physical properties of the Martian surface. Cambridge University Press. chapter 20. pp. 451–467.

Marlow, J., Martins, Z., Sephton, M., 2008. Mars on earth: soil analogues for future mars missions. Astronomy & Geophysics 49, 2–20.

Oravec, H., Zeng, X., Asnani, V., 2010. Design and characterisation of grc-1: A soil for lunar terramechanics testing in earth-ambient conditions. Journal of Terramechanics 47, 361–377.

Pacifici, A., 2009. The Argentinean Patagonia and the Martian landscape. Planetary and Space Science 57, 571–578.

Patel, N., Slade, R., Clemmet, J., 2010. The exomars rover locomotion subsystem. Journal of Terramechanics 47, 227–242.

Patel, N., Slade, S., Clemmet, J., 2009. Traction performance trials of the exomars rover breadboards, in: 11th Regional Conference of the International Society for Terrain-Vehicle Systems (ISTVS).

Perko, H., Nelson, J., Green, J., 2006. Mars soil mechanical properties and suitability of mars soil simulants. Journal of Aerospace Engineering 19, 169.

Peters, G., Abbey, W., Bearman, G., Mungas, G., Smith, J., Anderson, R., Douglas, S., Beegle, L., 2008. Mojave Mars simulant–Characterization of a new geologic Mars analog. Icarus 197, 470–479.

Scott, G., Saaj, C., 2009. Measuring and Simulating the Effect of Variations in Soil Properties on Microrover Trafficability.

Seiferlin, K., Ehrenfreund, P., Garry, J., Gunderson, K., Hütter, E., Kargl, G., Maturilli, A., Merrison, J., 2008. Simulating martian regolith in the laboratory. Planetary and Space Science 56, 2009–2025.

West, M., Clarke, J., Thomas, M., Pain, C., Walter, M., 2010. The geology of Australian Mars analogue sites. Planetary and Space Science 58, 447–458.