REGIONAL VARIATIONS IN PHYSICAL AND MECHANICAL PROPERTIES OF LUNAR SURFACE REGOLITH, Nicholas C. Costes, Space Sciences Laboratory, NASA/G. C. Marshall Space Flight Center, Huntsville, Alabama 35812

Because of the low ground contact pressure exerted by towed and powered wheeled vehicles used in lunar exploration, the mobility performance and tracks developed by these vehicles interacting with the lunar soil have provided a continuous record of the mechanical behavior of regolith material within the upper few centimeters of the lunar surface. This information, in conjunction with other lunar soil mechanics data, lends itself to analyses yielding quantitative estimates of the in-place consistency, packing characteristics and mechanical properties of this thin veneer of unconsolidated debris.

To date, three types of wheeled vehicles have operated on the lunar surface: The Modularized Equipment Transporter (MET) (1) which was used as a ricksha-type pushcart during the Apollo 14 mission; the three manned, self-propelled Lunar Roving Vehicles LRV-1, -2 and -3 (2) which provided surface mobility during the Apollo 15, Apollo 16 and Apollo 17 missions respectively; and the unmanned, self-propelled vehicle Lunokhod-1 which landed on the lunar surface aboard the Soviet spacecraft Luna 17 (3). Table 1 contains pertinent information on the mission, wheel characteristics and average wheel load under lunar gravity for each vehicle.

In spite of pronounced differences in the configuration and mode of operation of these vehicles, the average ground contact pressure per wheel for each vehicle was of the order of 0.5 N/cm². Also, careful examination of photographs obtained from each mission indicates that in spite of differences in local and regional geomorphologic conditions and material chemical composition encountered in each of these geographic locations, the magnitude and mode of deformation of the surficial soil interacting with the wheels of each vehicle were similar.

These facts alone are not sufficient to indicate similarity in the mechanical properties of the soil encountered in those missions because the resistance to penetration of the surface to such objects as a moving wheel depends on many factors, including the following: the physical and geometric characteristics of individual soil particles and their packing arrangement; the mechanical properties of the bulk soil mass; the depth to bedrock or to any relatively hard unconsolidated layers; the slope angle; the wheel characteristics and wheel slip. The relative influence of each of these factors on similar soil response indicated in two separate cases may be different in each case. However, on the basis of other data obtained in the course of lunar surface exploration, relating to the general nature, gradation, and mechanical behavior of lunar soil (4) and the thickness of the relatively loose, unconsolidated regolith material, it has been possible to estimate surficial lunar soil properties at the Apollo 14 site from MET tracks (1).

The procedure used for analyzing MET tracks, which was developed by the author, was based on (a) dimensional analysis relating to the performance of pneumatic tires on cohesionless granular soils, as applied to slightly
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cohesive crushed-basalt lunar soil simulants with similar grain size distribution characteristics as the lunar soil; (b) theoretical and experimental studies with lunar soil simulants under 1-g conditions, and penetration resistance tests on lunar soil simulants performed under simulated lunar gravity conditions aboard a KC-135 aircraft; and (c) bearing capacity theory. Analysis of LRV and Lunokhod track data was based in general on the same analytical procedure, modified to account for differences in wheel characteristics and mode of operation between the towed, pneumatic tires of the MET and the powered wheels of the LRV and the Lunokhod.

The results of this analysis has shown that in spite of variations in subsurface soil properties, as indicated by other investigations, there are no discernible differences in the properties of the surficial material between regions of different geologic age, origin and gross chemical composition. On the other hand, within regions of comparable geologic history and local environmental conditions there is a small but distinct difference between average properties of soil located in intercrater areas on level, firm ground and soil located on fresh crater rims, slopes and soft pockets or fillets. Average in-place material properties of these two main consistencies of surficial lunar soil are shown in Table 2.

The bulk density of the material $\rho_L$ can be obtained from the expression $\rho_L = G_S \rho_w/(1 + e)$, in which $G_S$ is the specific gravity of the soil particles and $\rho_w$ is the density of water. Although to date there is scarcity of data regarding the specific gravity of lunar soil particles from various locations on the lunar surface, available information (2), (3), (4), (5) indicates that it can vary from less than 2.9 to more than 3.2. The specific gravity of the terrestrial lunar soil simulant used in these studies was in the range 2.85-2.90.

In spite of differences which can be attributed to either local conditions or to averaging of material properties over depths greater than those associated with the development of tracks by lunar surface vehicles, the results of this analysis are in reasonable agreement with results reported by other investigators. The same material properties formed the basis of a lunar soil model which was used for extensive wheel-soil interaction studies that were performed during the development and mobility performance evaluation of the LRV (2). The remarkable agreement of data from the LRV performance and wheel-soil interaction during the Apollo -15, -16, and -17 missions with predictions made on the basis of the terrestrial wheel-soil simulation studies furnishes further corroborative evidence indicating that the average properties of the surficial lunar soil encountered during at least these three Apollo missions are as shown in Table 2. The cohesion of the lunar soil simulant determined from trenching tests at consistencies comparable to those at the same Apollo sites was in the range of 0.06 N/cm$^2$ to 0.29 N/cm$^2$.

On the basis of this study it appears that the initial consistency of surficial lunar soil resulting from major geologic events of relative short duration, is modified by steady-state, long-duration processes that tend to smoothen out initial differences and create a material with random variations in its mechanical properties which on a regional scale is statistically...
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homogeneous.

REFERENCES


<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Location</th>
<th>Distance Traversed (km)</th>
<th>No. of Wheels</th>
<th>Mode of Operation</th>
<th>Wheel Characteristics</th>
<th>Average Load Per Wheel in Lunar Gravity (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSL(1)</td>
<td>Fra Mauro</td>
<td>3.3</td>
<td>2</td>
<td>Pneumatic tire.</td>
<td>Diameter: 40 cm</td>
<td>Width: 10 cm, Section Height: 9 cm</td>
</tr>
<tr>
<td>LRV-1(2)</td>
<td>Hadley-Apennine</td>
<td>27.9</td>
<td>4</td>
<td>Wire-mesh, shaped as pneumatic tire with 50% of contact area covered with chevron-shaped tread.</td>
<td>Diameter: 83 cm, Width: 23 cm, Section Height: 19 cm</td>
<td></td>
</tr>
<tr>
<td>LRV-2</td>
<td>Descartes</td>
<td>27.0</td>
<td>Each wheel</td>
<td>Electrically powered.</td>
<td>Diameter: 51 cm, Width: 20 cm</td>
<td></td>
</tr>
<tr>
<td>LRV-3</td>
<td>Taurus-Littrow</td>
<td>32</td>
<td>8</td>
<td>Three spoked, rigid rims, interconnected with transverse cleats &amp; fine wire mesh.</td>
<td>Diameter: 51 cm, Width: 20 cm</td>
<td></td>
</tr>
<tr>
<td>Lunokhod-1(3)</td>
<td>Western &quot;coastal&quot; sector of Mare Imbrium</td>
<td>5.2</td>
<td>Each wheel</td>
<td>Electrically powered.</td>
<td>Diameter: 51 cm, Width: 20 cm</td>
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</table>

TABLE 1 Mission and Wheel Characteristics of Vehicles Used in Lunar Surface Exploration

<table>
<thead>
<tr>
<th>Soil Consistency</th>
<th>GL</th>
<th>Porosity</th>
<th>Void Ratio</th>
<th>D_r</th>
<th>B_TR</th>
<th>B_PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>0.15</td>
<td>47</td>
<td>0.09</td>
<td>30</td>
<td>30</td>
<td>36</td>
</tr>
<tr>
<td>Firm</td>
<td>0.76-1.35</td>
<td>39-43</td>
<td>0.64-0.75</td>
<td>48-63</td>
<td>39.5-42</td>
<td>37-38.5</td>
</tr>
</tbody>
</table>

GL - Penetration resistance gradient.
D_r - Relative density = (e_max - e) / (e_max - e_min), based on standard ASTM methods for determining e_max and e_min.
B_TR - Angle of internal friction, based on triaxial compression tests.
B_PL - Angle of internal friction, based on in-place plate shear tests.

TABLE 2 Average Material Properties of Surficial Lunar Soil

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