COMPARISON AMONG THE IN-SITU THERMAL PROPERTIES MEASUREMENTS ON INSIGHT AND PHOENIX AND LABORATORY MEASUREMENTS ON MARS REGOLITH SIMULANT.

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Introduction: The Phoenix mission was the first to measure the thermal properties of regolith of Mars in situ [1]. The Thermal and Electrical Conductivity Probe (TECP) was inserted to the surface regolith by the robotic arm of the spacecraft at 7 locations and obtained several repeated measurements of thermal conductivity and volumetric heat capacity for a duration of 1 to 2 sols at each location. Volumetric heat capacity is a product of density and specific heat. Nearly a decade later, the first heat flow measurement on Mars was attempted on the InSight mission [2]. The Heat flow and Physical Properties Package (HP^3), unfortunately, penetrated only ~35 cm into the regolith, not deep enough to obtain the thermal gradient representative of the heat flow from the martian interior [3]. However, HP^3 repeatedly measured in-situ thermal conductivity of the regolith over a duration of a Martian year and observed its seasonal variation [4]. The average of the thermal conductivities reported from Phoenix (0.085 W/m/K) is more than twice as that of InSight (0.038 W/m/K). Here we discuss possible implications of these results by also comparing them to laboratory measurements on Mars regolith simulant conducted under Mars-like atmospheric conditions.

In-situ Observations: Phoenix and InSight used different methods in their thermal measurements. Phoenix used the dual-probe heat pulse (DPHP) method [5] in which one of the probes (~2-mm diam., 1.5-cm long) emits heat and the other probe, 7 mm away, senses it as the heat conducts through the sample medium between them [6]. In this method, thermal conductivity and volumetric heat capacity of the medium can be determined from one experiment. InSight used a variant of the 'hot wire' method [7] in which one probe (~2.7-cm diam. ~40-cm long) emits heat and monitors its temperature as the heat dissipates away from it [8]. This method was also used for the Apollo Heat Flow Experiment [9]. The hot wire method can determine thermal conductivity only. It is possible to estimate volumetric heat capacity of the sample medium by performing a mathematical simulation of the experiment, but it involves a large uncertainty [2].

The regolith thermal properties reported by these two missions exhibited sensitivity to the temperature and the atmospheric pressure as expected previously by theoretical models [10]. The thermal conductivity of the regolith, monitored by HP^3, varied seasonally in sync with the atmospheric pressure of the InSight landing site (a range of 639 Pa to 761 Pa) [4]. When atmospheric pressure increased, so did thermal conductivity, and vice versa. This is because the heat conduction through the gas that occupies the pore spaces of the regolith became more efficient, as its pressure increased in sync with the atmosphere. On Phoenix, the TECP measurements, repeated multiple times over a sol, showed that both thermal conductivity and volumetric heat capacity of the regolith increased with temperature for a range of 190 K to 250 K [1].

Here we hope to identify the factors that contribute to the difference in thermal conductivities between the two missions.

Laboratory Measurements: Three batches of the Mojave Mars Simulant (MMS), which is pulverized basalt [12], have been measured for their thermal conductivity and volumetric heat capacity in a thermal vacuum chamber, filled with CO_2 gas, for the gas pressure (600 to 800 Pa) and temperature (240 to 253 K) comparable to those of the in-situ measurements by the two Mars missions. The thermal conductivity was measured by two methods (the hot wire and the DPHP) and the volumetric heat capacity was measured by the DPHP. For these measurements, commercially available probes (Decagon *KD2 Pro*) were used. However, because the thermal conductivities of the samples were an order of magnitude less than what these probes were designed for, the data reduction method was modified accordingly [13]. The three batches of MMS differed in their densities (1660 kg/m^3, 1540 kg/m^3, and 1230 kg/m^3) due mainly to a varying degree of compaction. The thermal properties obtained for the two higher density batches have been reported previously [13].

Observable Trends among the Thermal Properties: Figure 1 compares the atmospheric gas pressure-sensitivity of the thermal conductivity of the regolith of the InSight with that of the three MMS batches. They all show similar trends of thermal conductivity versus pressure with the former increasing by ~0.004 W/m/K per 100 Pa.

It is also noteworthy that the simulant batches with higher density tend to yield higher thermal conductivity values. Density of the regolith of the

InSight landing site has been estimated to be between 1007 kg/m^3 and 1211 kg/m^3 by numerical simulation of the conductivity measurement experiments [4].

Because these InSight measurements were obtained in a narrow range of temperatures (218 K through 227 K), no obvious sensitivity to the regolith temperature was detected. The thermal conductivity measurements repeated over a diurnal cycle at some of the Pheonix sites showed a linear trend increasing with temperature with a rate of 0.00033 W/m/K^2 [1].

The thermal conductivity values from InSight are less by ~0.012 W/m/K than the least compacted MMS (Fig. 1). The difference is too large to be explained as the effect of temperature difference (253 K vs. 218 to 227 K). If the difference in thermal conductivity is entirely due to their densities, regolith of the InSight landing site would be as light as ~800 kg/m^3.

Figure 2 shows the thermal conductivity versus the volumetric heat capacity for the Phoenix sampling sites and the 3 batches of MMS. The atmospheric pressures for the Phoenix sites at the time of these measurements are within a range of 735 to 775 Pa [1]. The thermal conductivity values for MMS have been adjusted to be equivalent (750 Pa), using the previously noted trend of 0.004 W/m/K per 100 Pa.

The Phoenix sites and the MMS batches show similar linear trends of their thermal conductivity increasing by 0.0038 W/m/K per 0.1 MJ/m^3/K. The variance of the volumetric heat capacities observed for MMS are due to that of their densities, while both density and specific heat likely varied among the Phoenix sites.

Discussion and Conclusions: For soil-like materials of similar composition, there can be clear correlations among thermal conductivity, volumetric heat capacity, and atmospheric pressure. The measurements from Phoenix show a clear trend between thermal conductivity and volumetric heat capacity (Fig. 2), and thus the regolith materials from the 7 sites are probably similar to one another. Both the Phoenix and InSight landing areas have been reported to be dominated by basaltic sands [14,15], but they have a large difference in thermal conductivity which is unlikely to be explained by the temperature or pressure sensitivity. One possibility is that the regolith of the Phoenix sites denser either by consisting of a greater proportion of higher-density minerals or cementation. It has been suggested that the regolith of the Phoenix landing site contains ~20% hematite, which is more dense and thermally conductive than basalt [1], even though occurrence of hematite in such a high concentration has not been reported from any other Phoenix investigations.

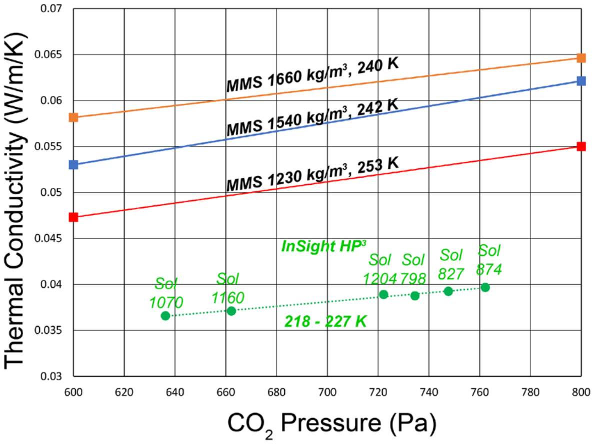

Figure 1. Thermal conductivity versus atmospheric pressure trends observed for 3 batches of MMS and the InSight landing site.

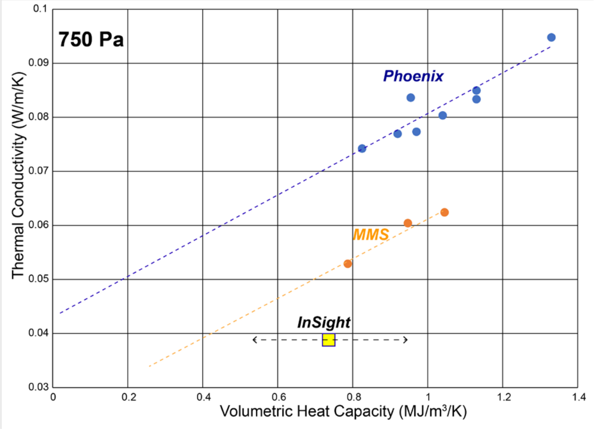

Figure 2. Thermal conductivity (adjusted for 750 Pa atmospheric pressure) versus volumetric heat capacity observed for Phoenix, InSight and MMS.

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