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Thermophysical property models for lunar regolith

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Abstract

We present a set of thermophysical property models for lunar regolith. Data from over 25 sources in the literature are integrated and fit with regression models for the following properties: composition, density, specific heat, latent heat of melting/fusion, thermal conductivity, electrical conductivity, optical absorption length, Gibbs Free Energy and Enthalpy of Formation. The models are based on data from Apollo samples and high-temperature molten regolith simulants, extending significantly beyond existing models in the literature. Furthermore, separate regression models are presented for Mare and Highlands regolith to demonstrate the effect of composition and to allow the models to be tailored to a wide range of applications. These models can enable more consistent, informed analysis and design of lunar regolith processing hardware and can also support lunar geological simulations. In addition to regression models for each material property, the raw data are presented to allow for further interpretation and fitting as necessary.

Keywords: Lunar regolith; Material property models; Electrical conductivity; Specific heat; Thermal conductivity; In Situ Resource Utilization

1. Introduction

Although the lunar surface missions during the Apollo and Luna programs brought over 380 kg of lunar samples to Earth, significant uncertainty remains concerning the material properties of lunar regolith. These uncertainties have often impeded rigorous engineering design and analysis of hardware designed to interact with lunar regolith, including reactors to perform In-Situ Resource Utilization (ISRU) (Linne, 2010; Schreiner et al., 2015), pneumatic and mechanical regolith transport devices (Mueller et al., 2010; Standish, 2010), and regolith excavation devices (Zacny et al., 2009). Furthermore, uncertainty concerning regolith material properties affects simulations of lunar geological evolution (Snyder et al., 1994) and predictions of the concentration of solar-wind implanted volatiles in lava flows (Fagents et al., 2010).

Although the Lunar Sourcebook (Heiken et al., 1991) and other lunar encyclopedias (Badescu, 2012) contain extensive data on lunar regolith, they focus on understanding the scientific theory behind regolith material properties. Additionally, many critical properties, including specific heat, thermal conductivity, and electrical conductivity are not discussed in detail. These sources present excellent compilations of the theory behind the trends seen in Apollo data, but do not serve as engineering references for accessible functional models of lunar regolith material properties.

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Here we present models for the density, specific heat, latent heat of melting, thermal conductivity, electrical conductivity, optical absorption length, Gibbs Free Energy, and Enthalpy of Formation of lunar regolith. These models are rooted in data from hundreds of minerals including Apollo samples and analogous materials published in over 25 articles in the literature. The models presented herein describe how regolith material properties depend on temperature, a critical aspect in many thermal-driven engineering applications, especially within the field of ISRU. To allow these property models to be used across a wide range of temperature regimes, the data and fits are not limited to solid granular regolith only, but also extend to the molten (liquid) state. Rumpf et al. (2013) noted that "[regolith] *properties have rarely been measured at temperatures greater than 350 K. Thus, the temperature dependencies of regolith properties must be extrapolated from measured values.*" By incorporating high-temperature data from lunar regolith simulants, we provide a measure of fidelity for high temperature applications.

Furthermore, the majority of the models presented herein are differentiated based on the type of lunar regolith. That is, separate models are presented for Highlands, High-Ti Mare, and Low-Ti Mare lunar regolith. This allows the models to be tailored to specific lunar applications, while also providing a degree of understanding as to how each material property is affected by regolith composition.

Although regression models are created for each regolith material property, the raw data from the literature survey are also presented in appendices so that additional analysis and data fitting may be performed as necessary.

2. Types of lunar regolith

Lunar regolith can be broadly classified into two categories: Highlands and Mare (Heiken et al., 1991). Highlands regolith is primarily comprised of ancient impact-shocked rock while Mare is comprised of basaltic lava flows in large impact basins (Crawford, 2014). Stoeser et al. (2010) further organized Mare regolith into High-Titanium Mare ($\geqslant$5 wt% TiO_2) and Low-Titanium Mare (<5 wt% TiO_2) classifications. Due to the differences in geological processes that resulted in Highlands and Mare regolith, the material properties and composition of these two types of regolith differ. This work largely differentiates regolith material properties between Highlands and Mare regolith. Where appropriate, models are further differentiated between High-Ti Mare and Low-Ti Mare regolith.

Lunar regolith is primarily comprised of plagioclase, pyroxene, olivine, and ilmenite, and the concentration of each depends upon location on the lunar surface. Mare regolith contains less plagioclase, but more olivine, pyroxene, and ilmenite (Heiken et al., 1991). Each of these minerals are composed of oxides, including iron(II) oxide (FeO), silica (SiO_2), alumina (Al_2O_3), titania (TiO_2), magnesia (MgO), calcium oxide (CaO), and trace amounts of other minerals and elements. Although the oxides are chemically bound together in various minerals, composition data is often presented in terms of the constituent oxides for simplicity. Oxide composition data from Stoeser et al. (2010) were averaged within each regolith type to generate a single value that represents the expected average oxide composition for each regolith type.

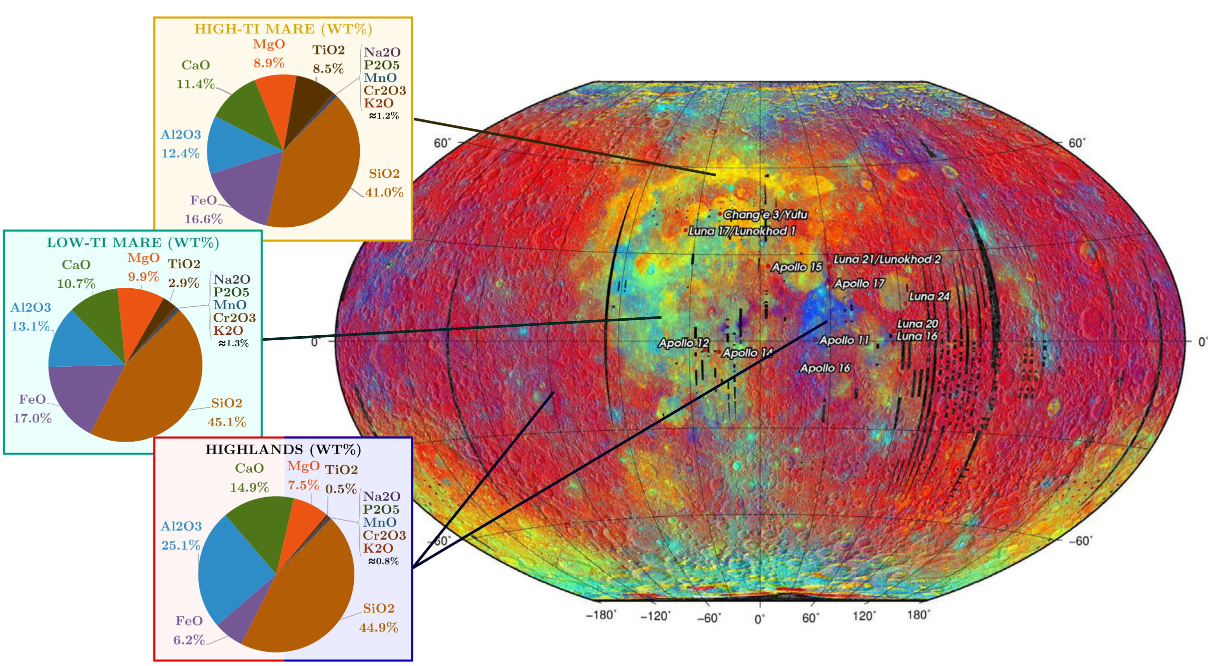

Fig. 1. The composition of three different types of lunar regolith: High-Titanium Mare (yellow), Low-Titanium Mare (cyan), and Highlands (older rock in red, younger rock in blue). Composition data from Apollo and Luna missions (Stoeser et al., 2010) and imagery data from Clementine UVVIS instrument (Lucey et al., 2000). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)