EFFECTS OF SAND GRAIN SHAPE ON THE SPECTRAL SIGNATURE OF SANDY LANDSCAPES IN THE VISIBLE DOMAIN

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ABSTRACT

In this paper, we investigate the effects of sand grain shape on the reflectance of sandy landscapes within the visible domain. Our investigation is supported by computer simulations performed using SPLITS (*Sp*ectral *Li*ght *T*ransport Model for *S*and) and taking into account actual sand characterization data. Our findings indicate that the spectral effects of grain shape may vary considerably depending on the distribution patterns of iron oxides present in sand-textured soils. These patterns and grain shape properties, namely roundness and sphericity, are largely determined by the formation processes of these soils. Hence, we believe that their interplay should be carefully taken into account in the retrieval of information about the mineralogy and morphology of sandy terrains.

***Index Terms*—** Sand, reflectance, grain shape, roundness, sphericity, simulation.

1. INTRODUCTION

The spectral reflectance of sandy landscapes, such as dune fields found in deserts, coastal regions and inland areas originally occupied by lake or sea beds, is significantly affected by the morphological characteristics of their constituent grains. These characteristics, in turn, are directly associated with the different formation processes of these sand-textured soils, notably through wind or water transport [1, 2, 3]. Accordingly, their spectral signature can be employed to infer information about their mineralogy and environmental history [4, 5]. Moreover, the integration of this spectral data with computer modeling techniques can also lead to the accurate prediction of future changes in sandy terrains [6].

It has been recognized that not only the size, but also the shape of the sand grains need to be taken into account in investigations relating the spectral signature of different sand soils to their formation processes and grain coating characteristics [1, 3, 7, 8]. Previous works in this area, however, focus on the effects of grain size on the reflectance of sand-textured soils [5, 9, 10]. In addition, when computer simulations are employed to investigate these effects, the grains are often represented by spheres [5, 9, 11].

In this work, we investigate how variations in the shape of sand grains may alter the spectral signature of sandy landscapes. Since geomorphological assessments of these terrains usually employ visual parameters such as color [4], our investigation is focused on the visible domain. Our observations with respect to these phenomena are supported by *in silico* controlled experiments performed using a predictive simulation set-up. Within this set-up, we assign different values to specific parameters, particularly those associated with the shape of the sand grains, and analyse their spectral effects while keeping the other parameters constant.

2. BACKGROUND

Soil grains are divided into three classes, or soil separates, namely sand, silt and clay, from the largest to the smallest particles, respectively [12]. The relative masses of each soil separate are compared to determine the texture of a soil sample. A sand-textured soil, henceforth referred to as sand soil, contains at least 85% sand-sized particles.

The shape of a soil grain is usually defined by two properties: roundness (R) and sphericity (S) [13]. While roundness can be described as the measure of detail in the features on the grain surface, sphericity refers to the degree to which the grain approaches a spherical shape. The expression "particle surface roughness" is often used to represent the combined contributions of sphericity and roundness to the grain shape.

Water-transported grains tend to have much smoother and uncoated surfaces than wind-transported (aeolian) grains due to continuous dissolution processes [1, 14]. Aeolian grains, on the other hand, tend to have rougher surfaces due to the saltation process. During this process, the grains are temporarily suspended by the wind before impacting the sand soil surface [14, 15].

Iron oxides, such as hematite, magnetite and goethite, can have a strong influence in the reflectance of sand soils, notably within the visible domain [7, 9, 10]. In fact, the presence of these minerals can be used to map the distribution of nutrients and heavy metals in sand soils on the basis of the surface reflectance of these terrains [4].

Iron oxides may occur as pure particles [7], as contaminants mixed with the parent material [16], or as coatings,

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within a kaolinite or illite matrix, formed on the grains during wind transport [1]. In terrestrial sand soils, the parent material is typically a material like quartz or calcite, with quartz (employed in this investigation) being the most common [9].

3. MATERIALS AND METHODS

Initially, we selected three sand samples whose spectral reflectance curves are provided in the U.S. Army Topographic Engineering Center (TEC) database [17]. These samples are originally from a red (hematite-rich) dune in Australia (TEC #10019201), a magnetite-rich site in Peru (TEC #10039240) and a dike outcrop in California (TEC #19au9815). Based on their descriptions [17], we assumed that the presence of clay-sized particles and moisture were negligible in these samples. The mean values used for their grain roundness (0.482), grain sphericity (0.798) and porosity (42.5%) were obtained from data provided in the literature [13, 18]. The remaining parameter values employed to compute modeled spectral reflectance curves for these samples are given in Table 1.

Parameters	Samples		
	Australian	Peruvian	Californian
r_{hg}	0.738	0.359	0.000
ϑ_{hg}	0.010	0.050	0.050
ϑ_m	0.000	0.170	0.000
s_a	85.00	92.80	85.00
s_i	15.00	7.200	15.00
μ_p	0.000	50.00	50.00
μ_m	100.0	0.000	0.000
μ_c	0.000	50.00	50.00

Table 1. Parameters used to obtain the modeled spectral reflectance curves for the Australian, Peruvian and Californian TEC samples [17]. The parameter r_{hg} corresponds to the ratio between the mass fraction of hematite to the total mass fraction of hematite and goethite represented by ϑ_{hg}. The parameter ϑ_m represents the mass fraction of magnetite. The texture of the samples is described by the percentages (%) of sand (s_a) and silt (s_i) particles. The particle type distributions considered in the simulations are given in terms of the percentages (%) of pure (μ_p), mixed (μ_m) and coated (μ_c) grains. It is assumed that magnetite appears as pure particles in sand soils characterized by the presence of this mineral [2, 19].

The modeled directional-hemispherical reflectance curves depicted in this work were computed using SPLITS (*Sp*ectral *Li*ght *T*ransport Model for *S*and) [20], and considering an angle of incidence of zero degrees. This model takes into account the individual morphological characteristics of the sand grains and their distribution in the pore medium (air or water). Note that the percentages of the sand-sized and silt-sized particles depicted in Table 1 are employed to compute their dimensions during the simulations using a particle size distribution provided by Shirazi *et al.* [12].

SPLITS can be run online via a model distribution framework [21] that enables researchers to specify simulation parameters (*e.g.*, angle of incidence, spectral range and sand characterization data) through a web interface [22], and receive customized simulation results via email. Hence, researchers can fully reproduce our results and extend our investigation to other experimental conditions.

It worth noting that although SPLITS provides bidirectional readings, one can obtain directional-hemispherical quantities (provided by our online system [22]) by integrating the outgoing light (rays) with respect to the collection hemisphere [23]. Similarly, bihemispherical quantities can be calculated by integrating the BDF (bidirectional scattering distribution function) values with respect to the incident and collection hemispheres [20].

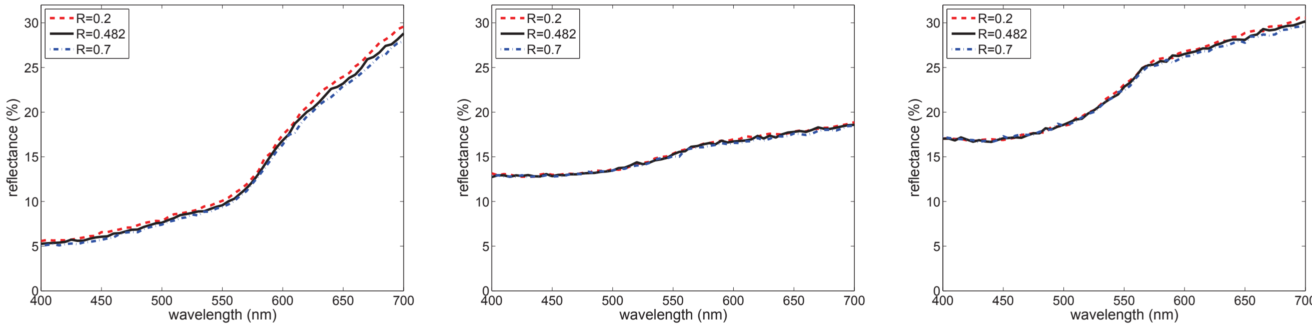
The root-mean-square errors (RMSE) calculated for the modeled (SPLITS) curves [20] with respect to their measured (TEC) counterparts [17] were 0.0137, 0.0048 and 0.0075 for the Australian, Peruvian and Californian samples, respectively. These low RMSE values indicate a good agreement with the measured curves. Accordingly, we employed these modeled curves as the control (baseline) curves for our *in silico* experiments involving grain shape variations. In our simulations, we considered minimum and maximum values for roundness (0.2 and 0.7) and sphericity (0.6 and 0.95) provided by Vepraskas and Cassel [13]. Note that R=0.7 corresponds to the smoothest grains, while S=0.95 corresponds to grains whose geometry is the closest to that of a sphere.

4. RESULTS AND DISCUSSION

The results of our simulations presented in Figures 1 and 2 suggest that the reflectance of sand soils is sensitive to variations in the sand grain shape, and this sensitivity tends to be higher in spectral regions characterized by higher reflectance values. They also suggest that the spectral signature of sand soils tend to be less sensitive to variations in roundness (Figure 1) than to variations in sphericity (Figure 2).

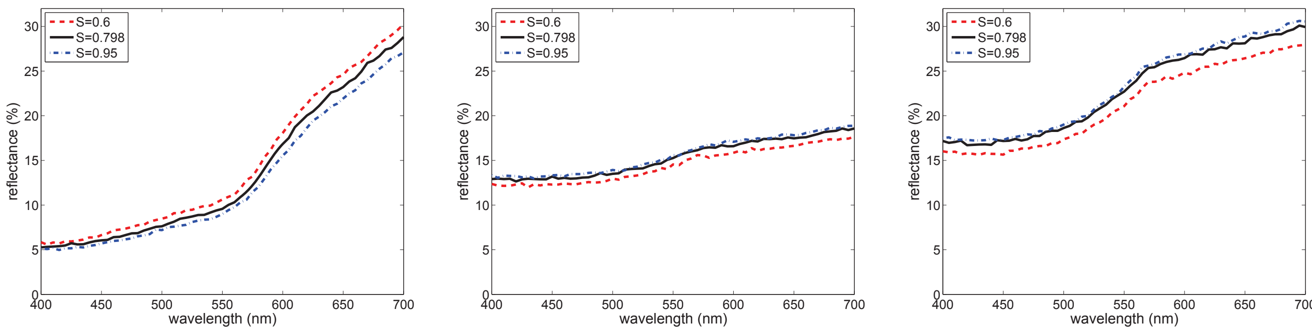
The more prominent impact of sphericity observed in our *in silico* experiments is consistent with the fact sphericity variations tend to have a more substantial influence on the probability of light absorption by the grains, which, in turn, has a larger impact in the overall reflectance of sand soils [4, 10]. Such an influence on light absorption is associated with changes in the pathlength of light travelling within the sand grains [20]. Roundness variations, on the other hand, tend to have a more substantial influence on the direction of light reflected on the surface of the grains [20].

Besides these quantitative differences, our *in silico* experiments also indicate qualitative differences in the effects of roundness and sphericity on the spectral signature of sand soils. More specifically, reflectance changes associated with increased roundness tend to be independent on how the iron



(a) Australian sample. (b) Peruvian sample. (c) Californian sample.

Fig. 1. Simulations of reflectance changes associated with minimum, maximum and mean roundness (R) values obtained from measured data [13]. Solid lines correspond to the baseline reflectance curves computed using the data depicted in Table 1.



(a) Australian sample. (b) Peruvian sample. (c) Californian sample.

Fig. 2. Simulations of reflectance changes associated with minimum, maximum and mean sphericity (S) values obtained from measured data [13]. Solid lines correspond to the baseline reflectance curves computed using the data depicted in Table 1.

oxide particles are distributed within the sand samples (Figures 1), while reflectance changes associated with sphericity variations may depend on the distribution patterns of these minerals (Figure 2). We remark that that the iron oxides may be present in pure form, mixed with the parent material or as a coating formed on the sand grains. Accordingly, examining the sphericity experiments more closely, one can note that the reflectance of a sand sample may decrease with increased sphericity when the iron oxides are mixed with the parent material (Figure 2a). However, one can also note that it may increase with increased sphericity when the iron oxides are distributed in pure form or as coatings (Figures 2b and 2c).

5. CONCLUSION

Our findings indicate that the shape of sand grains can have significant effects on the reflectance of sand soils in the visible domain. Moreover, although both shape properties, roundness and sphericity, contribute to these effects, the latter can have a more substantial influence on sand reflectance. In fact, our simulations have demonstrated that the representation of sand grains by spheres may lead to significant deviations from the actual spectral signature of sand soils.

Our *in silico* experiments also show that the influence of sphericity may vary depending on how the iron oxides are distributed within the sand soils. Since the shape of sand grains and the distribution patterns of iron oxides (in pure form, mixed or as contaminants) are directly connected with the geomorphology of sandy landscapes, their interplay needs to be carefully taken into account in the development of new soil investigation methodologies, particularly those based on the integration of remote sensing data with predictive computer modeling.

As future work, we plan to investigate the effects of soil porosity on the spectral signature of sandy landscapes under different illumination and moisture conditions. Moreover, we believe that the interdisciplinary investigation methodologies can result in significant advances not only in the retrieval of texture and mineralogical information from sand soils, but also in the current understanding of the origins of terrestrial and extraterrestrial sandy landscapes. Therefore, we also intend to enable the extension of our investigations to extraterrestrial sand soils by incorporating to our online simulation set-up their specific mineralogical characteristics such as the presence of different parent materials (*e.g.*, basalt found in Martian sands [15]).

6. REFERENCES

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