A photometric study of regolith intimate mixing with ice-like impurity

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Abstract Surfaces of solid solar system objects are covered by layers of particulate materials called regolith originated from their surface bedrock. They preserve important information about surface geological processes. Often regolith is composed of more than one type of particle in terms of composition, maturity, size, etc. Experiments and theoretical works are carried out to constrain the result of mixing and extract the abundance of compositional end-members from regolith spectra. In this work, we have studied photometric light scattering from simulated surfaces made of two different materials—one is highly bright quartz particles (average diameter 78.336 μm) and the other is moderately bright sandstone particles (average diameter 253.757 μm). The samples were mixed with varying proportions and investigated at normal illumination conditions to avoid the shadowing effect. Said combinations may resemble ice mixed regolith on various solar system objects, and therefore, it is important for in situ observations. We find that the combinations show a linear trend in the corresponding reflectance data in terms of their mixing proportion and some interesting facts come out when compared to previous studies.

1 Introduction

Light scattering from particulate surfaces is presently of great interest in various fields of science and engineering that include remote sensing applications (e.g., [30]), various geological studies (e.g., [25]), interpretation of astronomical observations on cometary (e.g., [32]), asteroidal (e.g., [28]), or planetary surfaces (e.g., [4]), and also in the study of organic cells in biology (e.g., [2]). In planetary sciences and solar system studies, the scattered sunlight from floating dust grains in a cometary coma plays an important role in determining their composition, structure, and size distribution which retain various information about the history and evolution of the object. However, objects like asteroids and terrestrial and icy planets do not exhibit a coma, rather dust or ice grains are present on the surface in the form of regolith. Light scattering from regolith is more complicated process than that of coma due to multiple scattering of light. Moreover, regolith grains are irregular-shaped and coarser than cometary dust grains, and regolith surfaces bear surface roughness and porosity which makes computational work more difficult. In addition to all the above, regolith may be a combination of two or more different kinds of regolith in terms of composition, particle size, maturity, etc. (e.g., [11]). For example, the impact of meteorites on bodies like asteroids may result in the mixing of materials at depth with that on the surface, and thereby, albedo and spectral properties get modified (e.g., [23]). In particular, mixing of high albedo fresh regolith with low albedo weathered regolith on small objects like Vesta is evident from Dawn mission [39]. 1 Ceres and 4 Vesta are both known to have an icy mantle and a bright crust which is probably a mixture of rocky dust (originated from meteorite impact) and water ice, thereby decreasing its albedo (e.g., [38, 41]). In the case of high albedo outer solar system icy objects, water ice regolith crystal on these bodies often gets mixed with various unknown impurities which absorb light strongly in the visible and UV region thereby altering the albedo and spectral features to a considerable extent [5]. In our neighborhood, reflectance data at 1064 nm from Lunar Orbiter Laser Altimeter (LOLA) on board Lunar Reconnaissance Orbiter reveal that the floor of Shackleton crater that is situated at a permanently shadowed region near Lunar south pole is brighter than surrounding terrain and nearby craters [50] explained this effect by considering a one-micrometer-thick layer consisting of 20% of surficial ice. [31] predicted the 6% of ice in its intimate mixture with regolith within Shackleton crater by neglecting porosity while 14% of the same by considering the effect of porosity. The ice-mixed soil is also evident on Mars from Mars Reconnaissance Orbiter data [19, 24] and even on the permanently shadowed region of Mercury from the variation in reflectivity detected by Mercury Laser Altimeter (MLA) on board MESSANGER spacecraft [37]. So, to detect the presence of ice and other brighter/darker impurities such as low absorbing silicates or high absorbing carbon...
compounds or contamination due to space weathering products in the primary regolith, laboratory-based observations, as well as theoretical modeling works, are both important.

In this work, we performed an experimental study to outline the constrains and suitable conditions in light scattering observations to detect ice-like impurity in planetary regolith. We used ‘sand stone’ powder as primary regolith analog and a highly bright sample of white quartz as ice analog. Some important observations come out when the results are compared with previous studies.

2 Background

Based on the homogeneity of mixing, regolith mixing can be mainly of two types—(i) macroscopic and (ii) microscopic or intimate [34]. In both of the above two types, grains of the two (or more) separate compositions remain isolated from each other. However, due to various weathering or geological processes, grains may get fused forming a different type of mixture called complex mixture (e.g., pyroclastics used by [44]). Another type of mixing may be a Linear mixture (or areal mixture) where the physical distance between the constituent particles is enough large so that they scatter light independently, and therefore, multiple scattering can be ignored in this case. Other mixing types may be ‘coating’—where particles of regolith are coated by another material, and ‘molecular mixing’—where mixing takes place at the molecular level [6].

From spectroscopic studies, it is known that, other than macroscopic mixture and linear mixture, no other mixing is expected to give linearity in reflectance spectra in general (e.g., [6, 40]). As far as photometric observations are concerned, in this case, light intensity (or reflectance) at a particular wavelength at different illumination and viewing angles is measured. Although an adequate amount of photometric experiments have been performed for single regolith analogs, this area remains vastly unexplored for mixing. Spectroscopic observations are performed at a given angle of illumination and viewing, and therefore, the extension of the results at other angular geometry is not necessarily correct. Photometric observations are required to understand the angular regime where a general conclusion can be made.

The resultant intensity is the sum of single scattering and multiple scattering. Single scattering may result in a linear combination of resultant intensity, whereas multiple scattering may contribute to some non-linearity in the result. However, there are other factors like porosity, surface roughness, etc. which may also take part in the result of mixing. Many experimental and theoretical modeling works have been conducted in the field of reflectance spectroscopy of intimate mixtures. Among them, [7, 8, 14–18, 20–22, 26, 33, 34, 40, 45, 48, 49] are important.

In general, intimate mixtures are not expected to give linear reflectance combinations in all cases. However, in some cases, linearity is possible and therefore important to be determined from experiments. In this work, we performed a photometric experiment on two regolith analog samples and their intimate mixtures to constrain the geometry conditions and other factors suitable for their linear combinations.

3 Instrumentation and data sampling

The experiment was carried out with a goniometric device which is schematically shown in Fig. 1b, and the scattering geometry is shown in Fig. 1a. A diode laser at 650 nm was used as the source of light, and the detector unit comprises of two silicon-based photo-sensors (NORPS12), viz. comparator and detector as shown in Fig. 1b. Comparator measures the irradiance of the laser beam after reflection from a transparent glass plate placed at an angle 45° to the laser ray (Beam Splitter in Fig. 1b) and remains fixed in its position with respect to the laser beam. The detector measures the intensity of light scattered by the sample at different angles from vertical. The photo-sensors are interfaced to the computer via a microcontroller unit and capable of recording data with 10 bit ADC resolution, and a Windows software was written to acquire the digitized data from the microcontroller and to perform numerous data sampling and processing tasks including geometric correction \((\cos i / \cos e)\) needed to calculate the intensity of the scattered light from the measured flux values. The type of reflectance under study, in this case, is called bidirectional reflectance [16] which is defined as the ratio between the intensity of scattered light along a particular direction to the irradiance of the collimated incident beam. In this case, the Detector measures intensity, whereas the Comparator measures beam irradiance. Both sensors read almost simultaneously (with 10 milli-sec. time lag). As the counts are proportional to the flux density at the sensors, \((\text{detector count})/\text{comparator count})\) gives a normalized intensity which may also be termed as uncalibrated bidirectional reflectance. Due to this direct measurement of laser irradiance by Comparator, inconsistency in the intensity measurement was reduced to within ±5%, which goes up to ±15% or even higher due to laser beam fluctuations without the use of this arrangement. Often intensity–count response of photo-sensors deviates considerably from the manufacturer specifications, and therefore, before starting the experiment both sensors were re-calibrated at the wavelength under consideration by using inverse square law of flux (i.e., from a point light source the sensor count (flux) should vary proportionally to the inverse of \((\text{distance})^2\)). In the present experiment, angle of incidence \(i\) (Fig. 1a) was kept fixed at 0°; however, it is possible to go up to 90° in both directions from zenith. The angle of emergence \(e\) (Fig. 1a) can be varied from about 0° to 90° on the free side and from 0° to a little less than the incidence angle on the laser beam side. The field of view of the detector is 2.2°, and maximum angular inaccuracies in \(i\) and \(e\) measurements are less than a degree.

Throughout the experiment, normal to the sample plane lies on the plane of scattering, i.e., tilt angle was always zero, and thus,
Fig. 1  

(a) Bidirectional reflection—SO is the incident ray, OD is the scattered ray toward detector, and ON is the normal to the sample surface. If angle between normal to the sample surface and scattering plane is zero, then $g = i + e$. 

(b) Schematic of goniometer device (for convenience of drawing angle of incidence is shown to be zero).

(c) The improved goniometer device [10]

The phase angle $g$ is equal to $i + e$ (Fig. 1a). The minimum phase angle that could be achieved with this instrument was $2^\circ$. All experimental observations at a particular geometry were averaged from more than 120 numbers of data acquired at an interval of 1 sec. Error bars in the data (Fig. 4) indicate $\pm 1.5\sigma$ value (where $\sigma$ is the standard deviation) in the data set. A large number of identical observations on a test surface at $i=0^\circ$ and $e=45^\circ$ taken on different days show that any single observation is within $\pm 5\%$ of their average value which may be considered a good level of accuracy in a light scattering experiment. However, at grazing viewing angles ($e \geq 70^\circ$) higher inaccuracy is possible due to signal to noise (flux goes lower noise remains same). All the reported data are relative to the intensity value for barium sulfate pressed surface at $i = 0^\circ$ and $e = 45^\circ$ which is known to be very close to a Lambertian surface$^1$ (Lambert reflectance $r_{\text{Lambert}} = \frac{\cos i}{\pi}$). Observation on $BaSO_4$ was taken every-time when new data set was to be collected in order to avoid any variation due to ambient conditions. With the above setup, very low albedo measurement (as for dark materials like graphite, gao meteorite, etc.) was not possible, and therefore, the work was limited to moderate and high albedo samples only. A comprehensive discussion of the theory and description of a subsequent and recently developed more sophisticated version of the instrument is described in [10]. Figure 1c shows the improved setup which differs from the test-setup in terms of more sensitive detector (photo-sensitive IC TSL237), microcontroller controlled arms, better angular resolution, digital clinometers in place of earlier analog clinometers for angle detection, etc. which are described in detail in [10].$^1$

$^1$ It is evident from [27] that $BaSO_4$, $MgO$ and Spectralon surfaces (which are widely used as perfect diffusers) are not perfectly diffusing in nature; Spectralon is only the closest substitute to a perfectly diffusing surface called a Lambert surface.
from Mie theory calculation at $D = 78 \, \mu m$ and ($\lambda = 650 \, nm$).

Table 1: Optical properties of water ice, quartz ($H_2O$) and alumina ($SiO_2$). Here $\omega$ is the single particle albedo [16] from Mie theory calculation at $D = 78 \, \mu m$ and ($\lambda = 650 \, nm$).

| Material       | $n$    | $k$     | $\omega$ | Crystal structure | Reference for $n$, $k$ |
|----------------|--------|---------|----------|-------------------|-----------------------|
| Water ice ($H_2O$) | 1.31   | $1.4 \times 10^{-8}$ | 1.00     | Hexagonal, Trigonal, Cubic | [47] |
| Quartz ($SiO_2$)  | 1.54   | -       | 1.00     | Trigonal          | [12] |
| Alumina ($Al_2O_3$) | 1.77   | $9.0 \times 10^{-6}$ | 0.99     | Hexagonal         | [9] |

4 Samples

Samples used in this experiment are—(i) highly bright and pure white quartz ($SiO_2$ crystal) powder of fine particles and (ii) relatively coarser gray sandstone powder (sandstone is a sedimentary rock typically composed mostly of silica with a small percentage of other compounds like oxides of aluminum and iron). Other samples were prepared from the intimate mixtures of the above samples in different proportions. While sandstone may mimic silicate abundant regolith found on many objects of our solar system and regolith originated from sedimentary rocks of Mars, the quartz can be a good substitute to icy regolith on many solar system objects because of its similar optical properties with ice as described below.

The scattering of light by homogeneous spherical particles (Mie theory) of a given size depends upon two factors—(i) complex refractive index $n+i.k$, where $n$ and $k$ are the refractive index and absorption coefficient, respectively, at the wavelength of observation, and (ii) size parameter of the particle $\pi.D/\lambda$, where $D$ is the diameter and $\lambda$ is wavelength, [46]. Materials of different chemical composition but similar optical properties as given above scatter light in the similar manner. For crystalline solids, crystal structure may play some role due to its anisotropic optical properties. However, other factors like particle shape and particle porosity also play some role in the scattering of light, but these are generally considered in mathematical simulations rather than experimental, because it is not easy to control these factors from experimental point of view. Table 1 summarizes the optical properties of water ice, quartz, and alumina - which was used by [36] to describe light scattering from icy satellites of the outer solar system.

The quartz can be used as a substitute to ice because of its low absorbance and crystal structure similarity to ice. The $k$ value for quartz at visible wavelength is not reported yet; however, [1] reported that absorption coefficient of quartz in the visible range is below detectable level. Water ice is very low absorbing in the entire visible range and naturally occurs in hexagonal structure on earth. However, cubic and trigonal structure of ice is also possible [13, 35]. Natural quartz is a trigonal crystal and also low absorbing like ice, which makes it a potential ice substitute at room temperature. In Fig. 2, we can compare the single scattering for ice, quartz, and alumina particles as calculated from Mie theory. The similarity suggests that they can be used as substitute to each other.

We use six samples as shown in Table 2. Since the amount of SS1 was quite limited, one of each combination could be prepared. All the samples were pressed gently in their respective sample tray to make a smooth surface (Fig. 3a). Shapes of the particles are irregular (Fig. 3b and c). Figure 3d shows their particle size distributions as obtained from the Sample Analysis Report from Central Salt & Marine Chemicals Research Institute, Bhavnagar, Gujarat, India. Table 2 shows all other known details of the samples.

Mixing of the samples was performed in an agitator for sufficient duration of time so that a uniform mixture was prepared. The extent of uniformity in mixing was tested by studying reflectance of the laser spot at different locations of the sample at a fixed angle of incidence and detector, which was found within the uncertainty of detection in all cases.

The porosity of the original samples (Q1 & SS1) has been calculated by using the relation given by Eq. (1) [42]

$$p = 1 - \frac{(m/v)}{\rho},$$  
(1)

where $p$ is the sample porosity, $m$ is the mass of the powdered sample within the container, $v$ is the volume of the sample within the container in powdered form and $\rho$ is the density of the original material in the solid form. The porosity of the mixed samples can be calculated by the same equation, but density $\rho$, in this case, will be a weighted mean of the two end-members which can be calculated as follows: Let us consider two materials-1 & 2 with solid density $\rho_1$ & $\rho_2$, respectively. Also, let $m_1$ & $m_2$ be the masses of the respective materials in the mixed sample so that the total mass of the mixed sample is $M = m_1 + m_2$. Thus, $P_1 = m_1/M$ & $P_2 = m_2/M$ give the weight fraction of two materials in the mixed sample, and in percentage, these give the abundance of the contributors. Now, if $v_1$ is the volume occupied by material-1 of mass $m_1$ in its solid form, we can write

$$m_1 = \rho_1 v_1$$
Or, $P_1 M = \rho_1 v_1$

Or, $\rho_2 P_1 M = \rho_2 \rho_1 v_1$  
(2)

similarly,

$$m_2 = \rho_2 v_2$$
Or, $P_2 M = \rho_2 v_2$

Or, $\rho_1 P_2 M = \rho_1 \rho_2 v_2$  
(3)
Fig. 2 Mie theory single scattering due to ice, quartz, and alumina at $\lambda = 650\,\text{nm}$ and diameter $D = 78\,\mu\text{m}$. For quartz, we consider $k = 0$ (pl. see text). The resonance peaks in the curves average out for a distribution of particles.

Table 2 Sample details

| Code | Sample | Mean particle diameter (volume weighted) | Origin | Porosity |
|------|--------|----------------------------------------|--------|----------|
| Q1   | Quartz (powder) | 78.336 $\mu\text{m}$ | Natural | 0.51 |
| SS1  | Sand stone (powder) | 253.575 $\mu\text{m}$ | Crushed | 0.45 |
| QS1  | 10%Q1+90%SS1 | - | - | 0.47 |
| QS2  | 25%Q1+75%SS1 | - | - | 0.45 |
| QS3  | 50%Q1+50%SS1 | - | - | 0.48 |
| QS4  | 75%Q1+25%SS1 | - | - | 0.48 |

1Percentages indicate (weight/total weight)×100

adding (2) and (3), we get

$$ (\rho_2 P_1 + \rho_1 P_2) M = \rho_1 \rho_2 (v_1 + v_2) $$

$$ Or, \frac{M}{(v_1 + v_2)} = \frac{\rho_1 \rho_2}{\rho_2 P_1 + \rho_1 P_2} $$

$$ Or, \frac{\rho_m}{P_2} = \frac{P_1}{\rho_1} + \frac{P_2}{\rho_2} $$

where $\rho_m$ is the weighted mean solid density of the mixed sample under consideration to be used in Eq. (1) to calculate porosity. The meaning of $m$ and $v$ in Eq. (1) remains unchanged. Porosity values in Table 2 were calculated by considering $\rho_{\text{quartz}} = 2.65\,\text{g/cm}^3$ [3] and $\rho_{\text{sand stone}} = 2.80 \pm 0.13\,\text{g/cm}^3$ (measured).

5 Results

The observations were carried out at normal illumination to avoid the shadowing effect. Apart from that, the angle of incidence is frequently zero during laser altimeter observations onboard spacecraft visiting various solar system objects, and therefore, this is an important observation condition. Reflectance data obtained from each of the samples in Table 2 are shown in Fig. 4. The curves show a similar trend at low phase angles but quite different at large angles. From these results, three observations can be pointed out—(i) At small phase angles (up to 10°), all the curves have a decreasing trend which appears to be the end trail of opposition effect. (ii) At large phase angles $\geq 70^\circ$, the reflectance phase curve of SS1 shows an increasing nature while that of Q1 shows a decreasing
Fig. 3  

a Two prepared samples of sand stone (SS1) and quartz (Q1) powders for observation.

b Microscope image of sand stone particles.  

c Microscope image of quartz particles.  

d Size distribution analysis of SS1 and Q1 is shown. The dotted lines indicate inter-quartile ranges (IQRs), and the filled circles indicate the median values. It should be noted that Q1 distribution is slightly bi-modal in nature.
trend which can be compared with Mie calculations for spherical particles with the Hapke formula [16] for a monodisperse medium as shown in Fig. 5. Since surface roughness is known to be related to particle size, it is expected to affect differently in the above two cases and hence the nature of phase curves at large angles. The curves of mixed samples are flattened in this region, which may be due to the combined effect of albedo and roughness variation.

(iii) In a region between 5° and 45° phase angle, most of the curves are nearly parallel and horizontal. Careful observation reveals that the reflectance in this region is linear with the proportion of sample mixing (Fig. 6). The reflectance of the combined sample can be calculated from their end members with the following relationship

$$r_{\text{calculated}} = r_{\text{SS1}} \times P_{\text{SS1}} + r_{\text{Q1}} \times P_{\text{Q1}}$$

Here $r_{\text{SS1}}, P_{\text{SS1}}, r_{\text{Q1}}, P_{\text{Q1}}$ are the reflectance and mass fractions of SS1 and Q1 in the sample, respectively, and $r_{\text{calculated}}$ is the theoretically calculated reflectance assuming linear combination for the intermediate sample with mass fractions of end members as used at the RHS of Eq. (5). In Fig. 6, experimentally measured values at constant phase angles have been plotted against calculated reflectance for phase angles ≤ 45°. The points clearly show a linear trend about the line of unit gradient, which means that calculated
Fig. 5 Mie scattering with Hapke formula for monodisperse medium with typical \((n, k)\) values for non-absorbing and moderately absorbing silicate materials. The shape of the curves varies slowly with \(n\) and particle radius in this region. Reflectance values are normalized to unity at zero phase angle.

Fig. 6 Calculated reflectance using Eq. (5) and measured reflectance values are plotted for mixed samples (last four items in Table 2) at different phase angles.

and measured values are in good agreement with each other. \(R^2\) regression analysis given by Eq. (6) yields a goodness of fit of 95.49%.

\[
R^2 = \left(1 - \frac{\Sigma(r_{\text{measured}} - r_{\text{calculated}})^2}{\Sigma(r_{\text{measured}} - r_{\text{mean}})^2}\right) \times 100
\]

here \(r_{\text{mean}}\) is the mean of all measured reflectance values shown in Fig. 6.

6 Discussion

Comparing the results of this experiment with previous studies, the following observations can be pointed out:

1. Working with mixed samples, in page 89 Cord et al. [8] concludes that “...(1) the textural roughness, essential for the accurate determination of mineralogical abundances”. However, they used reflectance data at a higher angle of incidence (e.g., Fig. 4 of [8]) where the shadowing effect comes into play. In our observation, we find that at normal illumination conditions and at a given wavelength of 650 nm, the reflectance values are linearly dependent on the abundance of their components at phase angles between 5° and 45° (Fig. 6). At higher phase angles, however, this behavior is destroyed (Fig. 4), which may be due to the hiding effect due to surface roughness, i.e., if we assume that the rough surface is like a hilly terrain, the valleys are visible at small viewing angle but not at large. Hence, it turns out that the knowledge of textural roughness on abundance determination may not be essential in all conditions. It is necessary to find out the spectral/viewing regime from more experiments where roughness plays insignificant role in light scattering results when it is related to the abundance determination of intimate mixtures.
Table 3  A comparison of sample data reported in [49] and this work, and their quantitative fit to the calculation results

| References | Sample combination (role) | Relative size \((\mu m/\mu m)\) | Reflectance ratio (impurity/primary) | \(R^2\) |
|------------|---------------------------|-----------------|----------------------------------|-------|
| [49]       | SPIPA-A (impurity) + JSC Mars-1 (primary) | 4.5/24 = 0.19 | 0.898/0.103 = 8.72 | 28.63 |
| [49]       | SPIPA-B (impurity) + JSC Mars-1 (primary) | 67/24 = 2.79 | 0.862/0.103 = 8.37 | -731.40 |
| [49]       | SPIPA-B (impurity) + Dark Basalt (primary) | < 1² | 0.862/0.070 = 12.31 | -4058.53 |
| This Work  | Q1 (impurity) + SS1 (primary) | 78/253 = 0.31 | 0.313/0.118 = 2.65 | 95.49 |

¹Data retrieved from Fig.4(e),(f) and Fig.8(a),(c),(d) of [49]. The reflectance is at \(\lambda = 650\ nm\) and 50° phase angle
²The average size for the Dark Basalt sample is not known (pl. see Discussion (2) in Sect. 6), but, as most of the particles are expected to be larger than 67 \(\mu m\), the ratio must be less than unity

Fig. 7  Calculated reflectance using Eq. (5) has been plotted against measured reflectance values for the three sets of intimate mixtures in [49]. Data were derived from Fig. 8a, c and d of [49] at the wavelength of 0.65 \(\mu m\)

(2) Yoldi et al. [48] and [49] experimented on real water–ice samples of two different particle sizes (i) SPIPA-A (4.5 ± 2.5 \(\mu m\)) and (ii) SPIPA-B (67 ± 31 \(\mu m\)), and their intimate mixtures with two primary regolith (i) JSC Mars-1 (24 \(\mu m\)) and (ii) Dark Basalt (50 wt% of the particles > 109 \(\mu m\) and 50% < 109 \(\mu m\)). Out of the above four samples, they used three combinations at different proportions as described in Table 3. Ref [48] concluded that bigger ice particles (i.e., SPIPA-B) are difficult to detect at low phase angles even if their abundance is as large as 75% in the primary regolith, and therefore, laser altimeters are not recommended for ice detection on planetary regolith. However, our results suggest that there may exist certain regime where brighter particles as impurity may even be possible to detect in terms of their abundance. From Table 3, it can be seen that it’s difficult to find out a critical condition in terms of relative size of particles or their reflectance ratio as they do not indicate a particular trend w.r.t. \(R^2\) regression factor (data used for regression are shown in Fig. 7). However, our samples can be distinguished from other in terms of particle size and reflectance ratio. The primary (SS1) or impurity (Q1) sample we used, both were the largest in particle size among all the four cases shown here and also the reflectance ratio was the least in this case. So, linearity in the reflectance may dominate when following two requirements are satisfied by the samples: (1) average size of the impurity particles is within a range of 70-80 microns, whereas that of the primary is within 200-300 microns, and (2) our tested samples do not highly contrast with each other in terms of brightness (Table 3), so for low contrast regime the linearity is valid as per our investigation if first condition is already satisfied. Nevertheless, the role of brightness to the said linearity needs further investigation. Since our observation is restricted to zero angle of incidence, it is important to point out that apart from reflectance measurements, laser altimeters are also used for topographic mapping of surfaces (e.g., [29]), and therefore, it is not hard to determine the slope angle of the target locations and hence the angle of incidence from the altimetry data.
7 Conclusions

In Sect. 4, we discussed how quartz can act as a substitute to ice particles at room temperature for experimental purpose. Thus, the result we obtained may be compared to extra terrestrial regolith where ice may be present as impurity. Apart from that, our results may also be valid for those extraterrestrial surfaces where brighter silicate particles (such as olivine, pyroxene etc.) are mixed with relatively darker primary regolith. Our observations are restricted to normal illumination and phase angles equal to and above 5°. So our conclusions will be valid only within the tested regime only and may not be generalized to the below 5° regime where a special phenomenon called opposition effect (a sharp increase in reflectance, pl. see [16] for details), is dominant. In addition to that, our experiment is limited to a given wavelength of observation (650 nm). Since the optical constants (absorption coefficient and refractive index) of materials undergo a great variability at different wavelength of light, the conclusion we draw is limited only up to the spectral range around 650 nm where the optical constants remain unaltered. Conclusions from this study can be summarized in the following points:

1. Unlike [8], our results suggest that textural roughness may not be essential for mineralogical abundance determination from an intimate mixture if the particles constituting the regolith satisfy the two conditions as described in Sect. 6. Also it is essential to note that the angular regime where this conclusion is valid is limited to $\epsilon \epsilon [5^\circ, 45^\circ]$ at normal illumination.

2. Our experiment shows that brighter particles mixed with relatively darker regolith may follow a linear reflectance combination in terms of abundance as given by Eq. (5). However, results reported by [49] show a different trend (Fig. 7). Therefore, it is essential to identify the constrains that determine the linear regime as that might be useful in the abundance determination of ice or other brighter impurities from regolith by using their reflectance data.

3. We find that particle size of the impurity and primary regolith both may play critical role in determining the linear regime. Besides this, the brightness contrast may also be important. At 650 nm of observation wavelength, results from [49] indicate that intimate mixture of 35% ice and 75% ice in Dark Basalt did not change the reflectance significantly (Fig. 7), whereas the contrast of brightness is quite high between these two materials (Table 3). However, in our experiment 10% quartz as impurity in sand stone alters the reflectance by a detectable amount, but the contrast between these two materials is much smaller (Table 3). Thus, it may not be generally true that a brighter impurity is easily detectable in a terrain if their contrast is high, rather the opposite case may also be possible.

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Author contributions Light scattering experiment was done by DD, whereas PC contributed to the sample PSD analysis.

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Data availability Data reported in this work are available to be used by anyone without restrictions.

Declarations

Conflict of interest No conflict of interest applicable

Ethical approval Not Applicable

Code availability Not Applicable
Appendix A

Data shown in Fig. 4 are shown separately (See Figs. 8 and 9).
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