Research Article

Developing Prototype Simulants for Surface Materials and Morphology of Near Earth Asteroid 2016 HO3

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There are a variety of applications for asteroid simulants in asteroid studies for science advances as well as technology maturation. For specific purpose, it usually requires purpose-specialized simulant. In this study, we designed and developed a set of prototype simulants as S-type asteroid surface materials analogue based on H, L, and LL ordinary chondrites' mineralogy and terrestrial observations of near-earth asteroid 2016 HO3, which is the Chinese sample return mission target. These simulants are able to simulate morphology and reflectance characteristics of asteroid (469219) 2016 HO3 and, thus, to be used for engineering evaluation of the optical navigation system and the sampling device of the spacecraft during the mission phase. Meanwhile, these prototype simulants are easily to modify to reflect new findings on the asteroid surface when the spacecraft makes proximate observations.

1. Introduction

Asteroid simulants are needed in supporting space missions, developing near-earth asteroids in situ resource utilization technology, and developing planetary defense techniques. It is unrealistic to create simulants that replicate all characteristics of the target asteroids due to different geological processes on asteroids and Earth [1]. Therefore, purpose-specialized simulant is more useful and practical for actual space missions that always have specific purposes, such as navigation experiment and sampling test [2].

The recent asteroid missions to Itokawa, Ryugu, and Bennu have acquired numerous high-resolution images of these asteroids. Observations show that small asteroids (less than kilometer-sized) are rubble piles, and up to tens of meter-sized boulders and submicron- to millimeter-sized regolith particles are exposed on their surface [3–5]. Such a characteristic brings unexpected challenges to spacecraft when selecting landing and sampling sites, as what Hayabusa 2 and OSIRIS-Rex have encountered. China will launch its first asteroid mission in the coming few years aiming to

first return samples back from a near-earth asteroid (469219) 2016 HO3 and then rendezvous with a main belt comet 133P/Elst-Pizarro or 311P/PANSTARRS [6]. Due to the very much unknown surface morphology and properties of 2016 HO3, it is highly likely that this mission will be facing great challenges during sampling operation. To reduce risks, evaluations should have been performed before the actual landing and sampling operations, which would ultimately provide valuable information about the surface condition. In this case, it is necessary to develop asteroid simulants that can simulate the morphology and reflectance characteristics of 2016 HO3. Meanwhile, such simulants for 2016 HO3 should be easily to modify to reflect new observations made by the spacecraft.

There are previous attempts to developing simulated materials for asteroids, most of which are concentrating on C-type asteroids. These simulants are usually based on carbonaceous chondrites plus remote observations of targeted asteroids, including a series of prototype simulants based on carbonaceous chondrites [7], simulant HCCL-1 for Bennu [8], and a simplified Ryugu simulant [2]. Simulants

for S-type asteroid are relatively less reported. A new Itokawa asteroid regolith simulant (called IRS-1) as an S-type asteroid was developed for China's upcoming asteroid exploration [9]. However, this simulant only contains fine grains ranging from submillimeter to centimeter, without larger-sized boulders.

This study designed and developed the morphology equivalent prototype simulants for 2016 HO3 that are with particle sizes ranging from micrometer to at least tens of centimeters. The goal of these simulants is to simulate a possible rubble pile morphology and the reflectance feature of the surface of 2016 HO3 so that they can serve practical uses during the mission preparation and operation phases, such as test and evaluation of navigation system and sampling device before the actual touchdown or landing operation. Furthermore, when the spacecraft's initial observation reveals a different size distribution of 2016 HO3 surface than our estimation, which is always the case, our simulants can be easily modified to reflect the new findings.

2. Observation of (469219) 2016 HO3

The near-earth asteroid (469219) 2016 HO3 was found on 27th of April 2016 by the 1.8 m Ritchey-Chretien telescope of the Pan-STARRS Project [10]. The current available orbital properties of this body were estimated through terrestrial observations spanning a data-arc of 5140 d or 14.07 yr, from 17th March of 2004 to 27th April of 2019. 2016 HO3 is classified as an Apollo asteroid moving in a low eccentricity ($e = 0.10$) and low inclination ($I = 7.77^\circ$). It orbits in a 1:1 mean motion resonance with Earth with a minimum orbital intersection distance of 0.03 AU.

The physical parameters of 2016HO3 are currently poorly constrained. One single light curve from April 2017 gives a magnitude $H = 24.3$ and a rotation period $= 0.467 \pm 0.008$ hr [11], suggesting it is a typical small fast rotator. The size of 2016 HO3 has not yet been firmly established, but it is likely about 40-100 m. Based on an assumed standard albedo for S-type asteroids of 0.20 and an absolute magnitude of 24.3, it measures 41 meters in diameter. A recent study by Reddy et al. [12] established a possible shape model suggesting that 2016 HO3 is likely an elongated asteroid, which has a b/a ratio smaller than 0.479. Color ratios derived from a low-resolution visible spectrum of 2016 HO3 suggest an S taxonomic type [11].

The particle size distribution and porosity of the regolith can be estimated if the thermal inertia or effective thermal conductivity of asteroids is known. However, the faintness of 2016 HO3 makes such an estimation almost impossible. Observations by the Hayabusa, Hayabusa 2, and OSIRIS-Rex spacecraft revealed that the surface morphology of small-sized asteroids (less than 1 km) is mostly covered by boulders and in some areas by regolith, which is different from larger asteroids that are mostly covered by fine-grained regolith [3, 5, 13]. 2016 HO3 is a small asteroid with a diameter of 40-100 meters. It is reasonable to assume that it has a similar rubble pile surface. Therefore, for this study, we consider the surface of 2016 HO3 is covered by boulders with sizes ranging from several centimeters to at least several

TABLE 1: Average modal abundances of ordinary chondrites (wt%, from [17]).

Class	H group	L group	LL group
Number of samples	18	17	13
Olivine	33.0	42.1	51.1
Low-Ca pyroxene	25.6	23.2	21.1
High-Ca pyroxene	6.7	8.1	7.4
Plagioclase	9.0	9.4	9.7
Troilite	5.8	7.2	5.7
Metal	18.2	8.4	3.5
Others ^a	1.7	1.6	1.6

^aNormative abundances of apatite, ilmenite, and chromite [18].

TABLE 2: Mineral recipe for prototype simulant of 2016 HO3 (wt%).

	QLS-1	QLS-2	QLS-3
Olivine	30	38.7	46.9
Low-Ca pyroxene	29.1	28.2	25.6
High-Ca pyroxene	3.2	3.1	2.8
Plagioclase	9	9.4	9.7
Pyrite	5.8	7.2	5.7
Fe metal	19.4	10.6	7.2
Ni metal	1.8	0.8	0.3
Others ^a	1.7	1.6	1.6

^aMixture of apatite, ilmenite, and chromite.

tens of centimeters and fine particles with sizes ranging from micrometer and millimeter.

3. Development of 2016 HO3 Simulants

Minerals are the basic building blocks of planetary materials, and thus, mineral-based simulants offer the closest potential match to the properties of actual asteroid materials [7]. Both telescopic observations and analyses on the returned asteroid Itokawa sample indicate that most S-type bodies have mineralogy similar to those of ordinary chondrites [14, 15]. Ordinary chondrite meteorites (OCs) are silicate-rich meteorites and by far the most abundant meteorites (80% of all falls) [16]. According to their iron content, these meteorites are divided into H (high total Fe), L (low total Fe), and LL (low total Fe, low metal) groups, with 42.8%, 47.4%, and 9.8% of OC falls belonging to each group, respectively. Composition measurements of H, L, and LL group OCs provide a reference model from which to develop simulated asteroid 2016 HO3 materials for current observations suggests an S-type asteroid. The modal mineral abundance results obtained by X-ray diffraction analysis on 18 H, 17 L, and 13 LL unbrecciated OC falls show that olivine and low-Ca pyroxene are the most abundant phases present, while plagioclase, high-Ca pyroxene, troilite, and metal comprise the remaining XRD-measured mineralogy [17]. It is not clear that which OC group 2016 HO3 belongs to, and thus, we developed three prototype simulants QLS-1, QLS-2, and QLS-3 corresponding to H, L, and LL OCs, respectively.

FIGURE 1: Production of 2016 HO3 prototype simulants. (a) Dry mixture of raw materials. (b) Paste after adding sodium metasilicate pentahydrate solution. (c) Dried fine and small-sized particles. (d) Large-sized boulders.

Table 1 lists the average modal mineralogy of the aforementioned H, L, and LL OC falls. The mineral recipes for the prototype simulants are based on these data, with some modification because of various trades involved in sourcing raw materials (Table 2).

To develop asteroid 2016 HO3 simulant, we obtained different types of raw rock or mineral materials from terrestrial mines, including olivine from Hannuoba area in Hebei Province, low-Ca pyroxene from Alashan area in Inner Mongolia Province, high-Ca pyroxene from Qingdao area in Shandong Province, and plagioclase from Shijiazhuang area in Hebei Province. Some raw materials are from commercial supplies, including powdery pyrite, metal iron and nickel, apatite, ilmenite, and chromite.

We first crushed the raw materials in chunk or other nonpowder forms into fine powders. Pyrite, metal iron, and nickel came from commercial suppliers as micron-sized powders and require no further processing. The average grain size of crushed powder materials is 50-100 microns. After having all raw materials processed, we mixed the powder material in the appropriate weight ratios (Table 2), resulting in homogeneous medium to dark gray powders (Figure 1(a)). Due to the absence of natural binders (clays) in the OC composition, we added sodium metasilicate pentahydrate (a.k.a. water glass) into the mixture, which polymerizes into a rocky binder under modest heat and the “pentahydrate” is released during polymerization. We dissolved sodium metasilicate pentahydrate in pure water and then mixed this solution with the dry mixture

(in a 1:5 ratio). The concentration of sodium metasilicate pentahydrate is 4-5% of the dry mixture. Then, the wet paste was dried in an oven under temperature at 150-160°C. When the paste lost all its water and formed solid blocks, we crushed them using hand tools, such as a wooden club, which results in a power-law particle size distribution [19]. The size distribution could be adjusted by sieving and mixing.

4. Characteristics of 2016 HO3 Simulants

We developed three prototype simulants with different abundance of iron and metal contents (QLS-1, QLS-2, and QLS-3), which accordingly represent asteroids linking to H, L, and LL type OCs (Figure 2). These asteroid simulant prototypes were characterized using scanning electron microscopy, X-ray fluorescence spectrometer, and VNIR reflectance spectroscopy.

The three S-type asteroid prototype simulants were imaged using a Zeiss Super 55 field emission scanning electron microscope (SEM) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS), with 15kV accelerating voltage. As shown in Figure 3, particles are subrounded to highly angular, with elongated, platy, and square shapes. Very fine particles ($<5\mu\text{m}$) adhere to the surfaces of larger ones. Larger particles include individual minerals and agglomerate of smaller particles.

The major element chemistry of the prototype simulants was measured and analyzed using XRF-1500 X-ray

FIGURE 2: Scanning electron microscope images of typical particles of prototype simulants of 2016 HO3. (a) Overview of H group prototype simulant QLS-1 particles in various sizes and shapes. The inset white square indicates where the image (b) is taken. (b) Zoom in of image (a) showing mixture of large and fine grains. (c) LL group prototype simulant QLS-3. (d) Fines coating the surface of a larger grain in the L group prototype simulant.

FIGURE 3: VNIR reflectance spectra of 2016 HO3 prototype simulants compared with asteroid 25143 Itokawa and S-type asteroids [21].

fluorescence (XRF) with RSD between 0.1 and 1% at IGGCAS, and the results are listed in Table 3. Compared to H, L, and LL OCs, the simulants have significantly lower TFe_2O_3 (Table 3), a consequence of using terrestrial low-Fe pyroxene and olivine as the raw material.

TABLE 3: Major element bulk chemistry of prototype simulants and ordinary chondrites^a.

Oxide	QLS-1	H group	QLS-2	L group	QLS-3	LL group
SiO_2	34.4	34.2	36.6	37.9	38.7	39.7
TiO_2	0.2	0.1	0.2	0.1	0.2	0.1
Al_2O_3	4.4	1.9	4.3	2.1	4.3	2.2
TFe_2O_3	27.6	35.4	22.0	29.5	18.7	26.8
MnO	0.2	0.3	0.2	0.3	0.2	0.4
MgO	20.8	21.8	24.1	23.8	26.9	24.8
CaO	5.6	1.6	5.6	1.7	5.7	1.8
Na_2O	0.7	0.7	0.7	0.9	0.6	0.9
K_2O	0.2	0.1	0.2	0.1	0.2	0.1
P_2O_5	0.4	0.2	0.3	0.2	0.4	0.2
NiO	2.4	2.0	1.2	1.6	0.6	1.4
Cr_2O_3	0.9	0.5	1.0	0.6	1.0	0.5

^aFrom [20].

Reflectance spectra of the prototype simulants were acquired at the China University of Geosciences (Wuhan), using a VERTEX 70v Fourier transform infrared spectrometer at ambient condition. The scattering configuration was approximately 45° - 45° biconical. The resulting spectra (0.500 – $2.5\mu\text{m}$) are shown in Figure 4, which offsets them for clarity. As shown in Figure 4, the measured spectrum of the three prototype simulants is broadly similar to the spectrum for asteroid Itokawa and S-type asteroids. Both samples have two strong absorption bands at ~ 0.9 – $1\mu\text{m}$

FIGURE 4: (a) The simulated rough surface using 2016 HO3 simulant and (b) the close-up image of the very rough surface of Itokawa [23].

and $\sim 1.9 \mu\text{m}$. The $\sim 0.9\text{--}1 \mu\text{m}$ mineral absorption band is the result of the presence of either pyroxene or olivine or both, while the $\sim 1.9 \mu\text{m}$ band is indicative of the presence of pyroxene [21]. Weak absorption bands at $\sim 1.4 \mu\text{m}$ are related to the OH stretching associated with structurally bound OH and H_2O , while the $\sim 2.2 \mu\text{m}$ and $\sim 2.3 \mu\text{m}$ absorptions may be due to metal-OH (e.g., Al-OH and Fe, Mg-OH) transitions, which is likely caused by vapor in the ambient environment and/or impurities in the raw materials.

5. Application

Our primary purpose for developing 2016 HO3 simulants is to reproduce the optical properties and a possible rubble pile structure of the surface. Since the morphology of 2016 HO3 is still unknown, asteroid Itokawa was chosen here as a reference. We sieved and mixed large boulders (several to several tens of centimeters) and smaller particles to match the size distributions of particles roughly following the power-law index as measured on Itokawa [4, 22]. The simulants were distributed in a Styrofoam container with the size of $1 \text{ m} \times 0.8 \text{ m}$. Comparison between images of our simulated topography and Itokawa surface demonstrates similar morphological characteristics (Figure 4). When the optical properties of 2016 HO3 are revealed by the initial observations of the spacecraft during the phase mission, our prototype simulants could be easily adjusted to match possible new and unexpected findings. Subsequently, the simulants could be used in optical navigation experiment and to study the efficiency of the sampler before its touchdown or landing.

6. Conclusion

We used remote observations of asteroid 2016 HO3 and modal mineralogy data from ordinary chondrites to develop three prototype simulants of S-type asteroids for engineering evaluation of the optical navigation system and the sampling device of the spacecraft. The size of the simulant particles ranges from tens of centimeter to micrometer. The characterizing results of the prototype simulants show similarity to their analogue meteorites

despite some discrepancies in bulk chemistry and reflectance spectra due to unavoidable factors in choosing terrestrial raw materials. These prototype simulants are easy to make and modify according to need.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Authors' Contributions

Yuechen Luo and Yuan Xiao contributed equally to this work.

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References

- [1] P. Metzger, D. Britt, S. Covey, and J. S. Lewis, *Figure of merit for asteroid regolith simulants*, vol. 11, article EPSC2017-436, European Planetary Science Congress, 2017.
- [2] H. Miyamoto and T. Niihara, "Simplified simulated materials of asteroid Ryugu for spacecraft operations and scientific evaluations," *Natural Resources Research*, vol. 30, no. 4, pp. 3035–3044, 2021.
- [3] T. Michikami, C. Honda, H. Miyamoto et al., "Boulder size and shape distributions on asteroid Ryugu," *Icarus*, vol. 331, pp. 179–191, 2019.

- [4] T. Michikami, A. M. Nakamura, N. Hirata et al., "Size-frequency statistics of boulders on global surface of asteroid 25143 Itokawa," *Earth, Planets and Space*, vol. 60, no. 1, pp. 13–20, 2008.
- [5] The OSIRIS-REx Team, K. J. Walsh, E. R. Jawin et al., "Craters, boulders and regolith of (101955) Bennu indicative of an old and dynamic surface," *Nature Geoscience*, vol. 12, no. 4, pp. 242–246, 2019.
- [6] J. Huang, X. Zhang, T. Wang, Z. Huo, X. Shi, and L. Meng, "Small body exploration in China," European Planetary Science Congress, 2020.
- [7] D. T. Britt, K. M. Cannon, K. Donaldson Hanna et al., "Simulated asteroid materials based on carbonaceous chondrite mineralogies," *Meteoritics and Planetary Science*, vol. 54, no. 9, pp. 2067–2082, 2019.
- [8] A. R. Hildebrand, L. T. J. Hanton, M. Rankin, and M. I. Ibrahim, "An asteroid regolith simulant for hydrated carbonaceous chondrite lithologies (HCCL-1)," *78th Annual Meeting of the Meteoritical Society*, vol. 1856, article 5368, 2015.
- [9] X. Zeng, X. Li, D. J. P. Martin et al., "The Itokawa regolith simulant IRS-1 as an S-type asteroid surface analogue," *Icarus*, vol. 333, pp. 371–384, 2019.
- [10] C. de la Fuente Marcos and R. de la Fuente Marcos, "Asteroid (469219) 2016 HO3, the smallest and closest Earth quasi-satellite," *Monthly Notices of the Royal Astronomical Society*, vol. 462, no. 4, pp. 3441–3456, 2016.
- [11] X. Li and D. J. Scheeres, "The shape and surface environment of 2016 HO3," *Icarus*, vol. 357, p. 114249, 2021.
- [12] V. Reddy, O. Kuhn, A. Thirouin et al., "Ground-based characterization of Earth quasi satellite (469219) 2016 HO3," *AAS/-Division for Planetary Sciences Meeting Abstracts# 49*, vol. 49, 2017 August 2021. <https://ui.adsabs.harvard.edu/abs/2017DPS....4920407R>.
- [13] O. S. Barnouin-Jha, A. F. Cheng, T. Mukai et al., "Small-scale topography of 25143 Itokawa from the Hayabusa laser altimeter," *Icarus*, vol. 198, no. 1, pp. 108–124, 2008.
- [14] T. Nakamura, T. Noguchi, M. Tanaka et al., "Itokawa dust particles: a direct link between S-type asteroids and ordinary chondrites," *Science*, vol. 333, no. 6046, pp. 1113–1116, 2011.
- [15] E. A. Cloutis, R. P. Binzel, and M. J. Gaffey, "Establishing asteroid-meteorite links," *Elements*, vol. 10, no. 1, pp. 25–30, 2014.
- [16] R. Hutchison, "Meteorites: A Petrologic," in *Chemical and Isotopic Synthesis*, Cambridge University Press, 2006.
- [17] T. L. Dunn, T. J. McCoy, J. M. Sunshine, and H. Y. McSween Jr., "A coordinated spectral, mineralogical, and compositional study of ordinary chondrites," *Icarus*, vol. 208, no. 2, pp. 789–797, 2010.
- [18] H. Y. McSween, M. E. Bennett, and E. Jarosewich, "The mineralogy of ordinary chondrites and implications for asteroid spectrophotometry," *Icarus*, vol. 90, no. 1, pp. 107–116, 1991.
- [19] D. L. Turcotte, "Fractals and fragmentation," *Journal of Geophysical Research: Solid Earth*, vol. 91, no. B2, p. 1921, 1986.
- [20] C. R. Fulton and J. M. Rhodes, "The chemistry and origin of the ordinary chondrites: implications from refractory-lithophile and siderophile elements," *Journal of Geophysical Research: Solid Earth*, vol. 89, no. S02, article B543, 1984.
- [21] R. P. Binzel, A. S. Rivkin, S. J. Bus, J. M. Sunshine, and T. H. Burbine, "MUSES-C target asteroid (25143) 1998 SF36: a red-dened ordinary chondrite," *Meteoritics and Planetary Science*, vol. 36, no. 8, pp. 1167–1172, 2001.
- [22] T. Michikami and A. Hagermann, "Boulder sizes and shapes on asteroids: a comparative study of Eros, Itokawa and Ryugu," *Icarus*, vol. 357, p. 114282, 2021.
- [23] P. Michel, "Formation and physical properties of asteroids," *Elements*, vol. 10, no. 1, pp. 19–24, 2014.