

Proposal of a new category of lunar regolith simulants: Reduced particle-density simulants that exhibit equivalent self-weight in Earth gravity to native regolith in lunar gravity

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ABSTRACT

Current “normal density” lunar regolith simulants used in Earth gravity can be viewed as a poor replication of bulk material handling behaviour of lunar regolith in lunar gravity. The six-times greater self-weight of such normal simulants on Earth compared to the Moon can be viewed as the underlying cause. The use of such normal simulants in Earth gravity as part of technology development for lunar use may fail to adequately predict lunar behaviour and result in sub-optimal outcomes. This paper proposes a new class of reduced self-weight lunar regolith simulants to minimise this issue.

The current work elaborates the case for this new class of lunar regolith simulants with reduced particle density of one-sixth native lunar regolith resulting in reduced self-weight. To justify further this approach a series of studies are reported to highlight the expected differences between the current and proposed simulant uses. First, analytical arguments are used based around Jenike theory and the concept of Bond Number to highlight expected differences. Second, Discrete Element Method simulation is used to show the expected difference in behaviour between the two simulants classes. Third, a laboratory breadboarded discharge hopper is used to demonstrate behaviour differences between normal and reduced self-weight simulants. Additionally, a list of requirements for such reduced self-weight simulants is proposed.

The work concludes that the proposed new class of reduced particle density lunar simulants appears to have value and should be further pursued by the relevant communities.

1. Introduction

In-Situ Resource Utilisation (ISRU) will be essential for future sustainable lunar surface activities [1]. A key feature of ISRU is the effective handling of granular or bulk materials, specifically lunar regolith and processed materials produced there from. Experience [2] shows that in spite of millennia of experience with bulk materials handling on Earth, obtaining efficient operation of processes that use bulk materials is challenging and often fails. Given this difficulty in Earth-bound applications, it must be expected to be even harder in lunar environments, and also the costs and consequence of poor implementation are more severe. The unique challenges posed by a lunar environment with reduced gravity, extreme temperatures, vacuum conditions, and the nature of lunar regolith itself, require tailored approaches for success.

Currently, the scientific and engineering communities are actively

engaged in early-stage R&D for future lunar surface systems and processes, including those underpinned by bulk materials handling such as ISRU [3–5]. To ensure these early-stage designs lead to functionally reliable implementation on the Moon, testing within simulated lunar conditions – particularly lunar gravity – is crucial. Appropriate fidelity simulation is critical to avoiding failures or unexpected performance issues once systems are deployed.

Access to facilities capable of simulating lunar gravity (such as parabolic flights and drop towers) is often limited due to cost, availability, capacity, and the short duration of simulated conditions they can provide [6–8]. These constraints hinder the ability to conduct adequate testing. Additionally, available lunar regolith simulants have been historically chosen to replicate spectroscopic, mineralogical, and chemical properties, placing less emphasis on simulating properties that govern bulk materials handling behaviour [9].

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This lunar simulation situation relating to bulk materials handling creates a risk that early-stage R&D will not fully address potential problems with designs early within the development pipeline because of the difficulty in accessing appropriate lunar simulation facilities. This could lead to sub-optimal performance, system failure, or the need for costly last-minute fixes once lunar systems are in use. To improve lunar simulation facilities, new approaches are needed that effectively replicate the influence of lunar gravity on bulk materials handling while addressing the deficiencies of existing simulation methods (i.e., cost, capacity, and availability) [10].

The authors propose the concept of using a new class of regolith simulants with significantly lower particle densities than native lunar regolith – ideally, with a particle density one-sixth that of lunar regolith. This would enable the simulant's self-weight under Earth's gravity to approximate the self-weight of lunar regolith under lunar gravity. It is anticipated that this would allow materials handling behaviour closer to lunar conditions to occur in a normal laboratory or laboratory vacuum chamber setting and avoiding the need to use parabolic flight or other costly and limited availability approaches to replicate lunar gravity. Therefore, such reduced-particle-density simulants would significantly improve access to appropriate lunar bulk materials handling simulation for the broader lunar R&D community.

As far as we know, there is no serious mention or expert community discussion about the principle of using reduced density simulants to replicate lunar self-weight in Earth gravity.

The remainder of this paper further explains and explores the case for reduced particle density regolith simulants. First, the case for a new class of lunar regolith simulants is made comprising simulants with one-sixth the particle density of lunar regolith (section 2). This is then demonstrated in following sections with analytical considerations (section 3), discrete numerical method simulations (section 4) and experimental breadboard tests (section 6). For the latter experimental test, initial proxies for final reduced particle-density simulants are identified (section 5).

2. The case for a class of lunar regolith simulants with one-sixth native particle density

This section introduces the concept of, and case for, a class of lunar regolith simulants designed with significantly reduced particle density compared to native lunar regolith. The basis for this concept lies in the need to pragmatically simulate the effects of lunar gravity on bulk material handling processes for future lunar surface operations but whilst in an Earth gravity environment. Reducing the particle density of the lunar regolith simulant by a factor of six while exposed to acceleration due to Earth surface gravity of $1g$ (9.81 m s^{-2}), will result in the same self-weight as a normal lunar particle density material would experience in a lunar surface gravity environment (1.62 m s^{-2}). This approach is targeted at a growing community of scientists and engineers developing technology for future lunar surface operations, where readily available and low-resource access to relevant bulk materials handling simulations can be expected to strengthen the relevant technology development workflow.

A significant reduction in self-weight experienced by bulk materials moving from Earth gravity to lunar gravity is a factor likely to heavily influence their handling characteristics [11]. Consequently, the need to simulate lunar gravity during early R&D activities becomes apparent. Currently, terrestrial simulation of lunar gravity is generally achieved through parabolic flight campaigns in aircraft and via drop towers. However, access to these facilities is often restricted. Financial costs associated with facility access, logistical complexities, scheduling limitations, long lead times for facility bookings and compliance with safety restrictions are common barriers. Additionally, parabolic flight opportunities for lunar gravity simulation are less common than microgravity. Equally important, available experimental capacity is limited by factors such as restricted experimental hardware mass and volume capacities,

and the brevity of the reduced-gravity periods (ranging from seconds in drop towers to tens of seconds in parabolic flights). This situation creates a hurdle for the lunar R&D community, as a significant fraction of this community lacks access to reduced gravity de-risking testing at the early stages of the development workflow. It is proposed that by implementing a suitable alternative simulation approach specifically tailored to bulk material handling, this access barrier could be reduced. Consequently, a larger portion of the community would be enabled to de-risk their activities earlier in the development process, potentially leading to more robust outputs and a greater return on the initial R&D investment.

To develop alternative lunar gravity simulation approaches for bulk materials handling, essential for the advancement of future lunar surface technologies and services and functions, the following requirements should be met. The approach shall avoid the prohibitive costs and logistical barriers often associated with parabolic flight and drop towers, ensuring wider access for the research community. To enable a wider range of testing and demonstrations, the approach shall support significantly longer experimental runs, ranging from minutes to hours or beyond. The simulation method shall accommodate larger experimental setups in terms of both volume and mass, again allowing for more complex and realistic testing scenarios. The approach shall facilitate the integration of additional lunar environmental factors (such as vacuum and potentially electrical charging), which are difficult to co-include in existing short-duration simulations on parabolic flights and drop towers. Finally, the method shall avoid the restrictive safety requirements typical of parabolic flight opportunities.

Assuming a new approach to simulating lunar gravity and its impact on lunar regolith handling properties seeks to avoid directly replicating lunar gravity itself, alternative methods for replicating the effect become necessary. If the influence of lunar gravity on bulk material handling properties of lunar regolith is primarily attributed to the force exerted by the weight of individual regolith particles (the product of particle mass and acceleration due to lunar surface gravity), then this force could be replicated under Earth gravity conditions by simply reducing the particle density of a suitable regolith simulant to approximately one-sixth that of actual lunar regolith. This is the fundamental hypothesis or basis of this approach – that a combination of Earth gravity and a lunar regolith simulant of approximately one-sixth the particle density of native lunar regolith will allow the replication on Earth, of the self-weight behaviour of lunar regolith in lunar surface gravity.

A suitable simulant for this new class of materials must consider bulk materials handling performance and broader usability issues alongside particle density. Key parameters affecting these characteristics include particle size distribution, particle shape, bulk density, and shear strength characteristics. Interparticle forces, particularly van der Waals interactions and electrostatic forces, significantly impact the flowability of fine-grained dry bulk materials like lunar regolith. Specific values and ranges for these parameters will be discussed later in this paper. For practical useability, simulants should also be: (i) readily available in suitable quantities with appropriate quality control and cost-efficiency, (ii) sourced from existing supply chains, (iii) minimal in their need for extensive pre-processing, and (iv) free of significant health, safety, or environmental hazards. Potential sources for such simulants include artificially manufactured lightweight aggregates, low-density volcanic rocks, expanded glass products, and various biologically derived materials such as wood flour, bio-abrasives (e.g., walnut shell grit) etc.

An important consideration in selecting a simulant is a consideration of the fidelity required to be of value. It is important to balance the desire for high-fidelity simulation with practical limitations. Researchers must carefully consider the required level of fidelity for a given experiment to guide the simulant selection process. It is also important to ensure a reduce particle density simulant is not used in applications where other properties not directly related to flowability of the simulant may be compromised. An obvious example is the particle strength which for reduce particle density simulants would be expected to be significantly reduced. This would mean that for high stress

applications such as high static and dynamic loadings including rover-regolith interactions, the simulants might compress and distort and change shape or fail.

The concept of reduced particle-density regolith simulants can be applied to simulate the effects of local gravity on bulk materials handling on other celestial bodies, such as Mars. To achieve a similar self-weight in an Earth testing environment, martian regolith simulants would require a particle-density approximately one-third that of native martian regolith.

3. Analytical consideration of the relevance of a reduced particle-density simulant in Earth gravity

This section considers established theoretical treatments for bulk materials handling to demonstrate that the proposed reduced density simulant used in an Earth gravity environment should replicate the bulk material handling behaviour in a lunar situation and differ significantly from the current community norm of using normal density simulants in Earth gravity. This will consider the Jenike's theory and the concept of Bond number. Note that this treatment assumes that the interparticle interactions associated with cohesion and particle geometry do not change significantly between Earth and lunar contexts.

3.1. Consideration of hopper discharge and Jenike's theory

The theory of Andrew Jenike, established in the 1960s, provides a commonly used framework for analyzing and designing hoppers to ensure reliable flow of bulk solids [12,13]. This theory is based on understanding the interplay between material properties (e.g., internal friction, cohesion), hopper geometry, and the stresses that develop during discharge.

Jenike's theory enables the prediction of various flow regimes that can occur in hoppers, which includes [13,14].

- Mass Flow: desired scenario where the entire material column moves uniformly downward, ensuring consistent discharge and minimizing segregation.
- Funnel Flow: undesirable regime where only a central channel of material flows, while the rest remains stagnant, leading to erratic discharge, and potential blockages and includes the concept of "ratholing".
- Arching and Bridging: problematic formation of stable structures within the material that block the outlet and prevent flow.

Central to Jenike's theory is the concept of the flow function, which quantifies the relationship between a material's shear strength and the consolidation stress it experiences. For the current work, the influence of gravity is directly related to the consolidation stress (also termed the normal stress), which is the weight of the overlying material. Hence, this stress is reduced by a factor of six when transitioning from Earth to lunar gravity for a given material. As this is related to the product of local acceleration due to gravity and the material particle density, if the particle density is reduced by a factor of six, the following resultant consolidation stresses (particle weights) are seen.

- Lunar gravity ($1/6g_E$) and lunar regolith (normal particle density (NPD)) – consolidation stress = $1/6g_E \times \text{NPD}$ (where g_E refers to the acceleration due to Earth surface gravity)
- Earth gravity ($1g_E$) and lunar regolith simulant (normal particle density) – consolidation stress = $1g_E \times \text{NPD}$
- Earth gravity ($1g_E$) and reduced particle density lunar regolith simulant ($1/6$ normal particle density) – consolidation stress = $1g_E \times 1/6 \text{ NPD}$

Hence, the proposed approach of the use of a one-sixth particle density lunar simulant in $1g_E$ on Earth results in the same consolidation

stress as expected for lunar regolith on the lunar surface. This contrasts with the current community norm, which is the use of normal density lunar regolith simulants in $1g_E$, which results in a six-times higher value of consolidation stress. It is acknowledged that particle density can play a role independent of acceleration due to gravity when particle inertia is involved, as in the pile formation from a discharging silo and so if this would expect to be a significant contribution to behaviour in a system, feature this would need to be considered.

Consolidation stress applied to the material at the bottom of a hopper from the head of material above has two effects: first it creates strength in the material, giving it a resistance to flow; secondly it drives the movement to produce flow. The balance between these two effects determines whether the material will flow or not flow, and as the relationship between consolidation stress and shear strength is non-linear, whereas the other relationship is linear, the balance between the two effects changes when consolidation stress alters. Therefore, the flow behaviour will be different when gravity changes. Hence, a reduction of a factor of six in the consolidation stress can be expected to have a significant impact on the properties of materials handling.

To highlight this effect, a well-known equation from Jenike's theory is given in Equation (1).

$$B_{\min} = \frac{H_{\alpha} \cdot \sigma_{c,\text{crit}}}{\rho_b g}$$

Equation (1): The Jenike equation [14] where $B_{\min}$ = powder arching dimension (i.e. minimum outlet size to allow reliable flow), H_{α} = geometrical factor to account for the shape of the hopper (cone, wedge or pyramid), σ_{crit} = critical stress, ρ_b = material bulk density, g = acceleration due to local gravity.

This relates to hopper design and relates the minimum hopper outlet diameter ($B_{\min}$) to the local acceleration due to gravity (g), the material bulk density (ρ_b), and the critical stress (σ_{crit}) – i.e. the stress at which shear begins for a given situation (the stress at which the two opposing effects described previously balance). This shows that for a given material and a given hopper that, a decrease in g from Earth gravity to lunar gravity will result in a six-fold increase in the minimum hopper outlet diameter required to obtain reliable flow. If a lunar regolith simulant with one-sixth particle density is used in Earth gravity, this will change the bulk material density by a factor of approximately six-fold. Note that this is only approximate as the bulk density is affected somewhat by gravity due to the reduced consolidation stress, however, the effect of the reduced stress on bulk density is in practice, small compared to the six-fold change in the self-weight of the bulk. For the critical stress, this is determined by a combination of consolidation stress and fundamental material properties relating to interparticle cohesion and particle geometry. Thus, for a low cohesion material (material with good flowability, defined as obtaining little strength due to the effect of consolidating stress) changing from Earth to lunar gravity will reduce the critical stress driven by the reduced consolidation stress to such an extent that the $B_{\min}$ value on the Moon is comparable to that on Earth. For a high cohesive material, while the consolidation stress decreases in lower gravity, the cohesive forces remain largely unchanged and dominate the contribution to the critical stress value. Therefore, the critical stress does not decrease as significantly as it does for low-cohesive materials. Therefore, the $B_{\min}$ value on the Moon is expected to be significantly greater than on Earth.

In summary, from a consideration of Jenike's theory and the changing gravity levels between Earth and Moon and regolith simulants with one-sixth the particle density of lunar regolith, it has been argued that one would expect a significantly different materials handling behaviour between Earth and Moon. By contrast, the use of a one-sixth particle density regolith simulant, should be able to replicate lunar materials' behaviour in lunar gravity environments, on Earth in $1g$, especially for cohesive simulants.

3.2. Consideration of bond number

Given the importance of cohesion on materials flow properties in low gravity, an alternative to consider is the Bond number. The Bond number (Bo) is a dimensionless number that compares the relative importance of gravitational forces to inter-particle attraction forces in a granular material [15]. A high Bond number ($Bo \gg 1$) indicates stronger attractive forces relative to gravity, suggesting the material may be more prone to arching and flow issues and a low Bond number ($Bo \ll 1$) indicates stronger gravitational forces relative to attraction, so that the material is freer flowing (less cohesive). It is a commonly used term in the terrestrial community, although somewhat less complex than Jenike's theory. In practice the forces of attraction for dry materials are mainly dominated by van der Waals forces, although electrostatic forces may be measureable for small particles using sensitive means such as the Mechanical Surface Energy Tester [16].

$$Bo = \frac{F_{cohesion}}{W_g}$$

Equation (2): Where Bo = dimensionless parameter Bond number, $F_{cohesion}$ = interparticle attraction force, W_g = particle weight due to gravity $W_g = (m \times g)$.

Inspection of the Bond number equation (Equation (2)) shows that the weight of a particle (W_g) is inversely related to Bond number (Bo), so a transition from Earth to lunar gravity would result in a six-fold increase in the Bond number and a possible transition from free flowing to non-free flowing. The use of a one-sixth density regolith simulant in $1g_E$ would reduce the weight of the material a similar amount and, therefore, result in a similar Bond number, and hence similar flow behaviour.

Therefore, consideration of Bond number leads to a similar conclusion that a one-sixth particle density regolith simulant would expect to be able to replicate aspects of bulk materials handling expected to be seen on the lunar surface with lunar regolith whilst in Earth gravity, and with significantly different expected behaviour to the commonly used normal density regolith simulants on Earth.

4. Discrete Element Method demonstration of the relevance of a reduced particle density simulant in Earth gravity

This section uses established Discrete Element Method (DEM) modelling to simulate a simple scenario of formation of “sandpiles” and determination of Angle of Repose (AoR) under Earth and lunar gravity conditions and with normal regolith or equivalent simulant particle density and reduced particle density simulant. The objective is to show that aspects of bulk materials handling behaviour on the lunar surface can be replicated more accurately in Earth gravity using a reduced particle density regolith simulant, and that this differs to the current community norm of using normal density simulants in Earth gravity. This will reinforce the argument that the use of reduced density simulants in Earth gravity is an appropriate and improved approach to take. Note that DEM simulation of flow and especially bridging/arching behaviour in hoppers was not attempted here due to computational limitations and known challenges in replicating this behaviour (bridging/arching) in DEM simulations [17].

4.1. Setup of the DEM simulation

The geometry of the 3D DEM simulations comprised a wedge hopper of 180 mm length and with a discharge slit opening of 10 mm width and 40 mm length. The hopper was pre-filled with particles in the simulation prior to opening the discharge slit and which allowed the particles to fall under acceleration due to gravity from a set height onto a flat circular surface 200 mm in diameter (Fig. 1). Note – the choice of a wedge hopper was influenced by physical hopper breadboarding activities reported later in this paper (Fig. 2).

For simplicity, material properties for particles used were selected

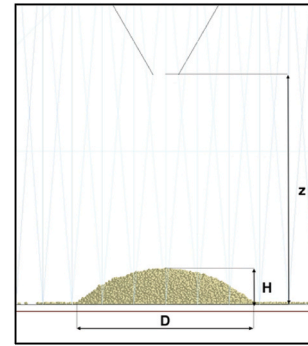


Fig. 1. Example of a DEM simulation upon completion of the simulation showing the formed sandpile and the hopper from which the particles were dropped. This is a cross-section of the 3D simulation. z is the particle drop height, H is the height of the sandpile and D the diameter of the base of the sandpile. To determine the angle of repose, the height, H , of the pile and half the diameter, $\frac{1}{2}D$, of the base of the pile are taken and the angle of the resultant right-angle triangle calculated.

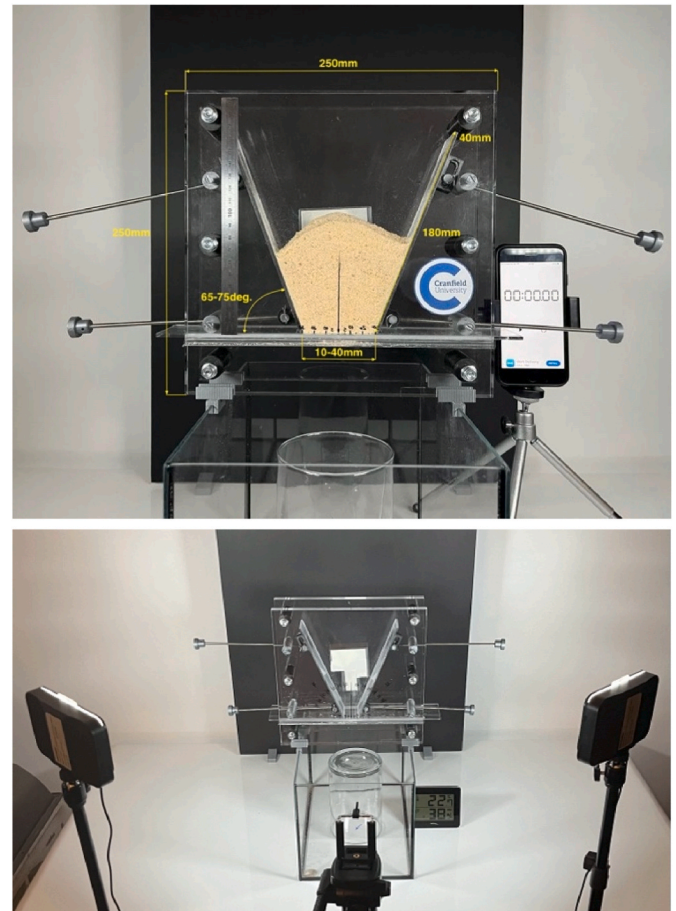


Fig. 2. Laboratory breadboard version of a wedge-shaped hopper with manually adjustable wall angles and manually adjustable discharge slit width. The projecting rods (2 on each side) are threaded and allow manual adjustment of the wall angles and the width of the discharge slot. There are two photographs of the breadboard setup – one of the details of the hopper (top image) and one zoomed out showing the lighting and camera setup (bottom image).

from pre-existing material libraries, specifically the Altair EDEM materials library of powders [18]. Selection was based on choice of materials with similar characteristics to those known from lunar regolith particles (high cohesiveness, low compressibility, angle of internal friction of

approximately 40°) and as determined from Apollo sample returns [19, 20]. Material ID-987 was chosen. The particle density was changed to match the two relevant scenarios of interest – a value of 3000 kg/m³ to represent normal density lunar regolith and lunar regolith simulants and 500 kg/m³ to represent a six-fold reduced density lunar regolith simulant. Additionally, AoR is strongly affected by coefficient of particle inner rolling friction, inner static friction, and restitution [21], therefore where these parameters of selected material ID-987 differed, they were replaced with values from the literature for lunar regolith simulant JSC-1A [22]. For particle geometry and to represent the typical non-spherical nature of lunar regolith particles, an elongated particle geometry comprising two overlapping spheres was chosen (sphere centers offset by half radius) which also limited the computational burden. A common, but unintuitive, aspect of DEM to address computational burden issues is to allow simulated particle size to be scaled-up by a significant factor without affecting the simulation outcomes [23, 24]. Hence within the simulation 1.0 mm diameter was used for the spheres in the elongated particle geometry.

For the physical model used in the simulation, the Edinburgh Elasto/Plastic Adhesion Model (EPPA) was chosen as it is well established for representing the behaviour of cohesive materials [25,26].

The DEM simulations were performed with Altair EDEM Discrete Element Method (DEM) software [18] running on a Nvidia RTX A5000 GPU.

A typical simulation comprised the following sequence. A rectangular virtual particle generator was positioned over the hopper. 24,000 particles were generated in a simulation period of 3 s at a rate of 8000 particles/sec. The generated particles were allowed to settle in the hopper for a further 1 s. The discharge slit was opened over a period of 0.5 s (horizontal sliding of a center-symmetrically splitting discharge slit door at 0.1 m/s) allowing particles to empty the hopper, falling onto the flat surface positioned at various distances below, and forming a pile (Fig. 1). Simulation finished after a total of 10 s allowing particles time to settle.

The AoR of the sandpiles from each simulation was determined by manually measuring the height and the width at the base of the cross-section of the elongated sandpile and then using simple trigonometry to determine the angle of the resultant isosceles triangle (Fig. 1)

5. Results and discussion

To compare the effect of two variables comprising different levels of gravity and different particle densities, a number of DEM simulations were performed. In addition, a third variable was used comprising the effective drop height of the particles from the hopper opening to a flat surface. The justification was the existing knowledge [27] that drop height, and hence particle kinetic energy, can affect the shape of sandpile formation and therefore the value of angle of repose. Common practice is to vary the drop height to identify height ranges (intermediate kinetic energies) where the angle of repose value is constant [27]. A total of nine simulations were performed covering all combinations of the three variables and their values: Earth and lunar gravities, 500

kg/m³ and 3,000 kg/m³ particle densities, and drop heights of 30 mm, 90 mm, and 180 mm. The results of the nine simulations are shown in Table 1.

The range of AoR values is between 16.0 and 26.5°. A value of 16.0° represents a material (ignoring gravity effects) with very free-flowing properties and a value of 26.5° one with less free-flowing properties. For the DEM simulations, the simple particle geometry chosen due to computational limitations is likely to be a significant contribution to the precise values of the AoR (rounded particles in practice give lower AoR) and if a more representative particle geometry was chosen (more angular or irregular), higher angles of repose would be expected [21]. Since the objective of the current work is to highlight differences between materials handling scenarios rather than absolute values, the simulation is still relevant.

The variation of drop height across the three scenarios of gravity and particle density resulted in similar trends in all three. The AoR values for the 30 mm and 90 mm drop heights are similar within a scenario and the AoR values from the drop height of 180 mm are lower in all cases. The consistency between the lower drop heights suggests that the AoR values are in a region where the kinetic energy variation is not influencing the AoR values. At a drop height of 180 mm, the reduced AoR values suggest the increased particle kinetic energy is sufficient to start influencing the AoR value. Therefore, only the AoR values from the 30 mm and 90 mm drop heights will be considered further.

The comparison of AoR values for normal particle density, i.e. normal density lunar regolith simulants and lunar regolith, in Earth gravity and lunar gravity shows a difference with values in Earth gravity of just below 20° and in lunar gravity of approximately 25°. Hence, an easily measurable difference is seen with the same materials exhibiting very free flowing behavior in Earth gravity and less free-flowing behavior in lunar gravity [28,29,31]. This indicates that under such conditions the use of normal density regolith simulants in Earth gravity is a poor replication of lunar behaviour.

The comparison of AoR values for reduced particle density in Earth gravity and normal particle density in lunar gravity shows little difference. Both sets of AoR values are approximately 25. Hence this indicates that using reduced density regolith simulants in Earth gravity appears to replicate the behaviour of lunar regolith in lunar environments (all other factors being equal) within the constraints of this limited study.

In summary, the DEM simulations support the view that reduced density simulants, reduce by a factor of six, used in Earth gravity are likely to give a more accurate representation of the lunar materials handling reality and both are significantly different to the common community use of normal density simulants in Earth gravity, which clearly does not represent lunar behaviour.

6. Consideration of simulant requirements, characterisation, and initial examples of reduced particle-density materials

This section advances the proposed approach of reduced particle density regolith simulants by considering three activities that, if pursued, are anticipated to lead to future availability and community use of reduced particle density regolith simulants: (i) First, to establish requirements for such simulants that include both material properties and operational needs requirements. (ii) Second, consider appropriate standardised methods to characterise physical and material handling properties of simulants. (iii) Third, consider initial examples of materials that can help advance and mature the understanding of the identification and selection of suitable simulants.

6.1. Consideration of requirements for reduced particle density regolith simulants

For any practical regolith simulant, the requirements can divide into two parts – (i) those that are relevant to the physical and chemical properties of regolith that are desired to be replicated and (ii) those

Table 1

Angle of repose (degree) values for different DEM simulations with variation of gravity level, regolith particle density and drop height. Each value is from a single simulation.

	Earth gravity normal particle density	Lunar gravity normal particle density	Earth gravity 1/6 normal particle density
30 mm drop	19.4	26.5	24.1
90 mm drop	19.6	24.5	23.9
180 mm drop	16.0	20.5	20

properties and features that relate to practical or operational useability. For any simulant, the reality is that compromises need to be accepted in terms of physical and chemical properties and their level of fidelity and often driven by practical and operational useability. An acceptable

compromise should be decided on a case-by-case basis, and the decision should be led by an understanding of the level of fidelity of simulation needed and a critical consideration of the specific features of interest.

Since the current focus is on the simulation of the materials handling

Table 2

Preliminary consideration of physical and chemical requirements for reduced particle-density regolith simulants for use in Earth gravity.

Bulk material features or properties	Relevance to simulation of bulk materials handling	Top-level requirement(s)	Example of requirement details	Validation
Particle morphology and morphology distribution (particle shapes)	Particle morphology influences static, sliding and rolling friction as well as cohesion with profound effects on bulk handling properties [13]. Lunar regolith typically has mixed particle morphology with rounded, angular/irregular, and dendritic components [30].	To replicate the particle morphology and morphology distribution of lunar regolith.	Shape and shape distribution of the particles (sphericity of the particles, Haywood shape coefficient [14].)	Determine particle morphology by physical techniques (e.g. microscopy including optical scanning)
Particle size and particle size distribution	Particle size affects particle cohesiveness with smaller particles allowing greater short-range interactions per unit mass due to higher Bond number. Lunar regolith is often dominated by fine particles in the hundreds of micrometer range and smaller, which in practical terms are fine enough to be cohesive.	To replicate the particle size and size distribution of lunar regolith.	Specify the required particle size and distribution as median particle sizes (D_{10} , D_{50} , and D_{90} values and the derived size span value $(D_{90}-D_{10})/D_{50}$).	Determine particle size by physical techniques (e.g. sieving, microscopy including optical scanning, light scattering)
Particle density	Determines the force of particle weight due to local gravity and is exhibited as a consolidation stress in bulk materials handling. Lunar regolith has particle densities determined by mineral composition with a weight that results from lunar gravity and is one-sixth of the weight of the same particle in Earth gravity.	To replicate the lunar weight of lunar regolith particles when used in Earth gravity.	Regolith simulants with particle density of one-sixth lunar regolith particle densities [32].	Determine particle density by physical techniques (e.g. gas pycnometer to determine particle volume, combined with weight measurement).
Particle cohesiveness	Interparticle forces affect bulk materials handling properties with Van de Waals and electrostatic forces dominant in lunar vacuum conditions. Lunar regolith small particle size allows significant contribution (higher Bond number) via increased particle surface area [30].	To replicate the cohesiveness of lunar regolith.	Regolith simulants with appropriate flow functions.	Determine particle cohesiveness by physical techniques (e.g. shear testing of samples or measurement of Bond number).
Particle compressibility	Particle compressibility affects bulk material handling by influencing flowability and packing density when stresses are applied and with these effects being amplified under higher gravitational forces. Lunar regolith has low compressibility, but some possible low particle density simulants have significant particle compressibility and will be used in Earth gravity which can result in exhibiting non-desirable behaviour. It is noted that particle compressibility is a complex behaviour which can involve elastic, plastic, and brittle particle deformation.	To avoid within simulant selection and testing/handling environment the emergence of non-lunar relevant bulk materials handling behaviour associated with particle compressibility.	To have a particle compressibility where no contribution to modifying bulk materials handling behaviour is seen.	Determine particle compressibility by bulk physical techniques (e.g. uniaxial compression testing, powder flow analysis).
Particle water content and capillary forces	Particle water content can affect bulk material handling properties through capillary forces, which can increase Bond number and hence cohesion, reduce flowability, and promote agglomeration, with these effects being amplified for small particle sizes. In a lunar regolith context, the presence of water and capillary forces is expected to be practically absent, but some possible low particle density simulants together with inappropriate environments (humidity) can result in exhibiting non-desirable behaviour although this is a greater or lesser problem depending on the particular materials and morphologies involved.	To avoid within simulant selection and testing/handling environment the emergence of non-lunar relevant bulk materials handling behaviour associated with particle water content and capillary forces.	To have a water content where no contribution to modifying bulk materials handling behaviour is seen.	Determine the water content (e.g. gravimetric analysis) and with the use of controlled drying and atmosphere humidity control to assure a water content low enough to avoid surface water and consequent capillary forces; the values are material dependent.

properties of regolith within a reduced gravity environment, the physical and chemical properties and requirements of simulants should focus on these properties. Therefore, in the context of simulating materials handling and lunar handling processes, consideration of other properties relating to simulant use cases such as mineralogical and spectroscopic properties and chemical reactivity in the context of ISRU are not relevant and will not be considered further. Furthermore, the emphasis throughout this work is on bulk materials handling properties and behaviour, and so relevance to the behaviour of lunar regolith in a dust context is not being considered here and would be expected to require a different approach to the requirements definition.

A preliminary consideration of the material requirements that reduced particle density regolith simulants should meet is given in Table 2. The table provides for each of six top-level requirements: the bulk material property or feature relevant to the requirement, a short commentary on the relevance of the requirement to bulk materials handling, a formal top-level requirement statement, example(s) of possible requirement details, and finally a consideration of how the meeting of the requirement could be validated. The six top-level requirements are related to the following properties: particle morphology, particle size and distribution, particle density, particle cohesiveness, particle compressibility, and particle water content and capillary forces. The requirements represent an initial set of obvious material requirements and are intended to be a starting point for the development of more detailed and quantitative requirements in future work. These preliminary requirements will be used as part of the selection process for preliminary examples of regolith simulants within a reduced particle density context that appears later in this section of the current paper.

For the operational requirements that reduced density regolith simulants should meet, preliminary consideration of the top-level operational requirements is given in Table 3. The table provides for each of the five identified top-level requirements: the operational property or feature relevant to the requirement, a short commentary on the requirement's relevance to use, or procurement, of reduced-density regolith simulant for bulk materials handling, and a formal top-level requirement statement. The five top-level requirements are related to the following features: simulant availability in sufficient quantities, simulant availability at acceptable financial cost, simulant availability with acceptable health and safety and environmental precautions burden, simulant availability with appropriate quality control and quality assurance, and simulant availability with appropriate characterisation of bulk materials handling properties. As for the previous materials requirements, the requirements represent an initial set of obvious operational requirements and are intended to be a starting point for the development of more detailed and quantitative requirements in future work. These preliminary requirements will be used as part of the selection process for preliminary examples of regolith simulants within a reduced particle density context that appears later in this section of the current paper.

6.2. Need for standardised characterisation methods for reduced particle density regolith simulants

As stated in the preliminary operation requirements for reduced particle density regolith simulants, there shall be a requirement for simulants to be characterised for bulk materials handling properties and behaviours by well-established techniques. The following is an initial consideration of characterisation techniques that could fulfil this need. For the three identified techniques, each will be considered via the following: the property or behaviour to be measured, relevance to bulk materials handling, the underlying basis of the technique, and a specific example of the technique. These techniques will be used as part of the selection process for preliminary examples of regolith simulants within a reduced particle density context that appears later in this section of the current paper.

Particle size, size distribution and morphology are core properties of

Table 3
Preliminary consideration of operational requirements for reduced particle-density regolith simulants for use in Earth gravity.

Operational features or properties	Relevance to use of reduced-density regolith simulant for bulk materials handling use cases	Top-level requirement(s)
Availability in sufficient quantities for a diversity of use cases.	A diversity of community usage is expected to range from use of gramme quantities at the laboratory bench to use of cubic metre quantities in “lunar yards”.	To be available in sufficient quantity for various use cases.
Acceptable financial cost.	The financial cost of an amount required for a given use case should be compatible with available financial budgets.	To be available at acceptable financial cost for various use cases.
Acceptable health and safety and environmental precautions or burdens during usage.	For a material to be used in a given setting, any local regulations or best practice for the material usage should not create a significant burden in terms of operational and/or bureaucratic consequences.	To not have any major health and safety and environmental handling concerns or burdens for various use cases.
Appropriate level of quality control and quality assurance.	Materials should have a level of consistency of properties and behaviours so that results from the materials usage can be appropriately compared within research groups and between research groups.	To have availability of appropriate level of quality control and quality assurance.
Appropriate characterisation of bulk materials handling properties.	Materials properties and behaviours should be characterised by a common set of established and readily available bulk materials handling techniques (discussed elsewhere in this section of this paper) so that such knowledge can be used by users to help choose appropriate simulants and design their use.	To have appropriate characterisation of bulk materials handling properties.

any bulk material. Such properties have profound effects on the handling behaviour of bulk materials in terms of static packing and flowability. Laser light scattering/diffraction is a well-established technique for rapid characterisation of particle size, size distribution and is therefore an obvious choice to provide such characterisation. A specific example of such a technique is the Mastersizer 3000 produced by Malvern Panalytical (UK). Morphology (shape) is usually measured by optical scanning (e.g. the Malvern G3 Morphologic).

Particle density is the core aspect of the current work, with the need to have regolith simulants with reduced particle densities of ideally a six-fold reduction compared to native lunar regolith. It is important to emphasize that particle density is the property of interest in formulating a reduced density regolith simulant and not the bulk density which is the combination of particle density, and any voids present in a bulk sample. Particle density can be determined by measuring particle volume, and in combination with gravimetric analysis, the particle density can be determined. Gas pycnometry is a well-established technique to

determine particle volume via gas displacement and the pressure/volume relationship given by Boyle's Law for a sample in a sealed chamber [33]. A specific example of such a technique is the Ultrapyc1200 produced by Quantachrome (now owned by Anton Paar, Austria). It is noted that for particles possessing sealed internal pores, gas pycnometry determines a particle density based on the combined volume of the solid material and these inaccessible internal pores.

Within the bulk material handling community, the concept of the flow function of a bulk material is well-established. The flow function describes the relationship between the resistance to flow (unconfined compressive strength) of a material and the stress previously applied to compact it [13,14]. It is the key parameter in understanding and predicting the flow behaviour of bulk materials in various situations. The flow function is typically determined experimentally using shear testers, which measure the shear stress at different consolidation levels. The resulting data is used to develop a flow function curve, which plots the unconfined compressive strength of a compact of the powder, against the compaction stress used to make the compact. The shape of the flow function curve can provide valuable insights into the flow properties of a bulk material. For example, a steep curve indicates a very cohesive material, while a flatter curve suggests a more free flowing material. A specific example of the technique is the Brookfield Powder Flow Tester (PFT) (AMETEK Brookfield, USA) which utilizes a rotary shear cell.

It is anticipated that additional characterisation techniques will be considered in future work.

6.3. Initial selection of materials to advance understanding of reduced particle density regolith simulants

To advance understanding of reduced particle density regolith simulants, here we identify an initial number of materials to help with exploring and refining the workflow that will lead to future identification of suitable simulants. It is important to note that these initial materials are not expected to be the recommended future reduced density simulants, but rather as examples to help refine the requirements, selection, and characterisation workflows for future simulants. As part of this approach, the initial materials will be used to demonstrate the concept of reduced particle density simulants in a discharge hopper breadboard activity later in this paper.

Selection of initial materials was influenced pragmatically by the existing availability of materials and experience at the Wolfson Centre

for Bulk Solids Handling Technology, University of Greenwich, UK. A limited number of materials was identified with consideration of the requirements given in Tables 2 and 3. Therefore, ready availability from existing supply chains, particle size, particle density, particle morphology, and particle cohesiveness/flowability were the key features considered. From this, five materials were identified. Out of these, two sets of two materials had the same underlying material composition, but different particle size distribution.

The five selected materials are summarized in Table 4 in terms of their relevance to early use to explore aspects of the reduced particle density simulants.

The initial materials chosen to allow materials handling properties to be explored are primarily focused on properties of (i) particle density and (ii) flowability/cohesiveness. All are readily available from existing supply chains at modest cost, none have high sensitivity to humidity, restrictive health and safety or other operational restrictions. The Eskal materials offer two levels of flowability and cohesiveness with particle densities similar to lunar regolith. Granulac materials offer two levels of flowability and cohesiveness with particle densities one-half of lunar regolith materials. Wood flour offers a level of poor flowability and high cohesiveness with particle density one-quarter of lunar regolith materials. This range allows comparisons between the current community use of normal density simulants (represented by Eskal) with the effect of reducing the consolidation stress contribution to materials handling behaviour (Granulac and wood flour) that is the basis of the reduced particle density simulant approach. The variation of flowability within the chosen materials allows the influence on materials handling behaviour of other particle properties, (independent of particle density/consolidation stress), such as particle morphology and particle interlocking and particle cohesion to also be observed.

The selected materials do not have a one-sixth density example. This resulted from a combination of a pragmatic choice given locally available materials and knowledge, that the current work is focused on developing the workflow to be used later to select more appropriate simulants. It is anticipated that in future work, a range of materials will be explored that are expected to have more suitable particle densities. These could include hollow glass particles, other biomaterials - e.g. walnut shell powder, plastic powders, porous natural materials - e.g. volcanic pumice, or porous manufactured materials - e.g. spray dried or expanded powders.

As described earlier, the materials properties relevant to bulk

Table 4

The characteristics and justification of the five initial selected materials to help with the refinement of the selection workflow for future reduced particle density simulants. *Particle density determined by gas pycnometry and gravimetric analysis, [§]particle size determined by laser light scattering/diffraction, [&]flowability is a qualitative observation from flow function determination. The materials were sourced as follows: Eskal materials manufactured and supplied by KSL Staubtechnik GmbH, Germany, Granulac materials manufactured and supplied by MEGGLE GmbH & Co. KG, Germany, and wood flour (Manufacturer reference nr. IT01465) from Supreme Products (UK).

Brand name or common name	Substance	Supply chain/common usage	*Particle density (kg/m ³)	[§] Particle size D ₅₀ (µm)	^{&} Flowability	Relevance to reduced density consideration
Eskal 10	Calcium carbonate	Used as an industrial filler/extender, abrasive, in construction and agriculture [34].	2800	10	Good flowability/low cohesiveness.	Eskal has similar particle density to lunar regolith and can act as a "normal" density control – available in range of particle size distributions. Larger particle size distributions have low cohesion/good flowability.
Eskal 500	Calcium carbonate	As immediately above.	2800	4	Poor flowability/very cohesive.	As immediately above. Smaller particle size distributions have high cohesion/poor flowability.
Granulac 70	Lactose	Used widely in food and pharmaceutical industries [35].	1558	90	Good flowability/low cohesiveness.	Granulac is a readily available material with reduced particle density (approximately one-half) compared to lunar regolith. Larger particle size distributions have low cohesion/good flowability.
Granulac 230	Lactose	As immediately above.	1558	24	Poor flowability/cohesive.	As immediately above. Smaller particle size distributions have high cohesion/poor flowability.
Wood flour	Wood (cellulose, hemicellulose, lignin)	Used as a filler in plastics production, bulking agent ... [36].	750	197	Poor flowability/very cohesive.	Wood flour is a readily available material with reduced particle density (approximately one-fourth) compared to lunar regolith. Has high cohesion/poor flowability.

materials handling behaviour should be characterised for any proposed simulants. For the five materials identified, the set of characterisations proposed of particle sizing, particle density, and flow function determination has been performed. The experimental details and full datasets will be reported elsewhere. The summary of the particle sizing, particle densities and flowability is given in Table 4.

In summary, top-level requirements for, and workflow to identify, future reduced density simulants have been produced, and five materials identified for immediate use to help evolve the requirements definition and workflow. These materials are used in the next section to practically explore the reduced particle density concept in a hopper laboratory breadboard.

7. Physical hopper breadboard demonstration of reduced particle density simulants in Earth gravity

This section describes the use of the materials and simulants identified in the previous section both normal particle density materials (Eskal) and early versions of possible reduced particle density materials (Granulac and wood flour) in the emptying of a laboratory breadboard of a hopper when in Earth gravity. This is to further demonstrate the difference in materials handling behaviour between existing approaches to simulate lunar materials handling using normal particle density regolith simulants in Earth gravity and the proposed use of reduced particle density regolith simulants to better represent real lunar behaviour.

7.1. Experiment design, hopper breadboard, and simulant materials

Elsewhere, a laboratory-breadboard version of a concept for a wedge-shaped hopper with manually adjustable wall angles and manually adjustable discharge slit width has been developed. The maximum volume capacity is approximately 300 cm³. This breadboard includes lighting and video recording to capture discharge behaviour (see Fig. 2). The hopper breadboard was used with the five materials described in the previous section (Eskal 10, Eskal 500, Granulac 70, Granulac 230, wood flour) to observe the ability of the materials to discharge from the hopper breadboard in Earth gravity. A dataset of discharge behaviour was collected as a function of three different hopper wall angles (65°, 70°, 75°), four different discharge slit widths (10 mm, 20 mm, 30 mm, 40 mm), three different sample mass loadings (50g, 100g, 150g) and with four replicates of each combination. A single hopper discharge experimental run consisted of the following: cleaning the hopper from previous use; pre-condition the hopper walls if a new material is used by filling and emptying the hopper three times with the new material, set the hopper wall angles and discharge slit width; load the hopper with a pre-weighed sample via a sieve placed at a set height above the hopper to control with some reproducibility the loaded sample consolidation; manual opening of the discharge slit; record the discharge as the fractional mass discharged. The hopper was used in a normal laboratory environment with an ambient temperature of around 21°C and a relative humidity of 40–60 % and without any preconditioning of the five materials.

The discharge behaviour, as the final mass fraction of material discharged, ranged between 100 % discharge and 0 % discharge with intermediate levels simplified and recorded as less than or greater than 50 %. Intermediate discharge was due to bridging behaviour which resulted in fractions of the material remaining stably in the hopper. Examples of the various behaviors are shown in Fig. 3. The final dataset (shown in Table 5) captures the range of experimental variables and color codes the results based upon the four different categories of discharge behaviour to allow ready visualisation of the overall trends in a qualitative manner.

In all cases, a mass flow discharge regime was observed given the following considerations. The specific wedge-shaped hopper geometry used in these experiments (with half-angles from the vertical between 15° and 25°), coupled with key material properties determined in supporting studies, were evaluated using Jenike's design charts for wedge-shaped hoppers. These properties included the effective angles of internal friction for the tested granular materials typically in the range from 35° (at high consolidation stress) to 60° (at low consolidation stress) - determined using a Brookfield shear cell, bulk density, typically in the range of 800–1200 kg/m³ and the angles of wall friction against the polymethylmethacrylate hopper surfaces, typically 17° (at high consolidation stress) and 25° (at low consolidation stress) - measured using a Jenike's wall friction tester. Using Jenike's methodology, the critical stress was evaluated, being in the range from 0.12 kPa to 0.4 kPa. Following on the critical arching dimension were calculated (around 40 mm for the worst-case material i.e. wood flour). This analysis consistently indicated that mass flow - where all material is in motion during discharge - would be the prevailing flow pattern [12,13,38]. A detailed presentation of the flow property characterisation is omitted for brevity but confirms the design of the experimental setup was conducive to this flow regime.

8. Results and discussions

The dataset of the hopper discharge behaviour for five different materials under a variety of hopper and other parameter settings is shown in Table 5. The dataset highlights two extremes – the Eskal 10 material which shows complete discharge for all experimental parameters (i.e. free flowing) and wood flour that shows no discharge or partial discharge for the majority of the experimental parameters (i.e. very cohesive with only 7 of the 144 parameter combinations showed complete discharge). The other materials show behaviour intermediate between these extremes with a trend of flowability increasing (and therefore cohesiveness decreasing) from Eskal 500 (low flowability) to Granulac 230 to Granulac 70.

For the various hopper parameters, the effect of varying the width of the hopper discharge slit is significant with all materials, apart from Eskal 10, showing no discharge with the smallest opening. For increased opening sizes, the trend is for increased partial to full discharge following the expected trend of flowability with Eskal 10 and Granulac 70 having the least cohesive nature, Granulac 230 intermediate and Eskal 500 and wood flour having the most cohesive nature. For the limited range of hopper wall angles chosen and based upon community

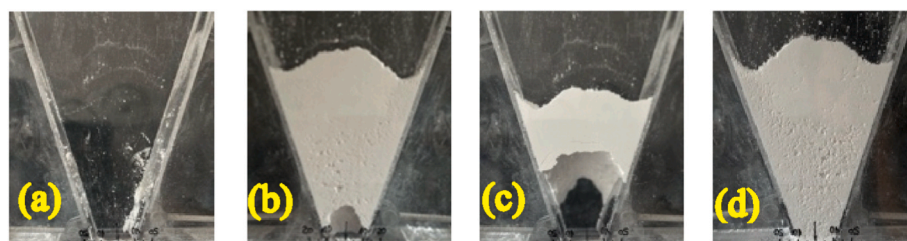


Fig. 3. Different mass fraction of hopper discharge from left to right: (a) complete or 100 % mass discharge, (b) less than 50 % mass discharge, (c) more than 50 % mass discharge, (d) no or 0 % mass discharge.

Table 5

Results of experimental hopper tests with different materials Eskal, Granulac and wood flour. Presented are examples of the four different types of discharge behaviour recorded. (a) complete or 100 % discharge – colored dark green (b) more then 50 % mass discharge – colored light green, (c) less then 50 % mass discharge – colored orange, (d) no or 0 % discharge – colored red. In additions, markings inside the cell's states: OK – complete discharge, X – no discharge and B – bridging with noted amount of mass discharged from the hopper in grams.

Eskal 10		65° wall angle				70° wall angle				75° wall angle			
		[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm
50g added	1. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	2. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	3. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	4. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
100g added	1. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	2. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	3. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	4. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
150g added	1. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	2. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	3. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
	4. sample	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Eskal 500		65° wall angle				70° wall angle				75° wall angle			
		[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm
50g added	1. sample	X	B(1.5 g)	B(37.3 g)	OK	X	B(3.2 g)	B(19.3 g)	OK	X	B(14.4 g)	OK	OK
	2. sample	X	X	B(28.4 g)	OK	X	B(3.4 g)	B(26.4 g)	OK	X	B(11.5 g)	OK	OK
	3. sample	X	B(2.4 g)	B(9.0 g)	OK	X	B(2.0 g)	B(22.0 g)	OK	X	B(6.7 g)	OK	OK
	4. sample	X	B(2.7 g)	B(12.7 g)	OK	X	B(3.8 g)	B(11.5 g)	OK	X	B(10.2 g)	OK	OK
100g added	1. sample	X	B(2.3 g)	B(20.4 g)	OK	X	B(3.5 g)	B(15.1 g)	OK	X	B(6.4 g)	OK	OK
	2. sample	X	B(2.6 g)	B(31.5 g)	OK	X	B(3.6 g)	B(35.8 g)	OK	X	B(3.8 g)	OK	OK
	3. sample	X	B(1.8 g)	B(20.2 g)	OK	X	B(3.4 g)	B(30.6 g)	OK	X	B(8.6 g)	OK	OK
	4. sample	X	X	B(15.7 g)	OK	X	B(2.9 g)	B(22.5 g)	OK	X	B(5.2 g)	OK	OK
150g added	1. sample	X	B(3.5 g)	B(37.4 g)	OK	X	B(3.9 g)	B(32.7 g)	OK	X	X	B(91.2 g)	OK
	2. sample	X	B(4.7 g)	B(68.0 g)	OK	X	B(3.3 g)	B(34.8 g)	OK	X	B(4.5 g)	B(75.3 g)	OK
	3. sample	X	B(6.2 g)	B(10.4 g)	OK	X	B(2.8 g)	B(41.3 g)	OK	X	B(8.3 g)	OK	OK
	4. sample	X	B(3.7 g)	B(55.3 g)	OK	X	B(3.1 g)	B(39.3 g)	OK	X	X	B(79.8 g)	OK

Granulac 70		65° wall angle				70° wall angle				75° wall angle			
		[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm
50g added	1. sample	X	B(7.4 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	2. sample	X	B(13.6 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	3. sample	X	B(5.7 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	4. sample	X	B(7.3 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
100g added	1. sample	X	B(11.9 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	2. sample	X	OK	B(85.5 g)	OK	X	OK	OK	OK	X	OK	OK	OK
	3. sample	X	B(13.2 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	4. sample	X	OK	OK	OK	X	OK	OK	OK	X	OK	OK	OK
150g added	1. sample	X	B(14.5 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	2. sample	X	OK	OK	OK	X	OK	OK	OK	X	OK	OK	OK
	3. sample	X	B(8.5 g)	OK	OK	X	B(8.0 g)	OK	OK	X	OK	OK	OK
	4. sample	X	B(10.7 g)	OK	OK	X	OK	OK	OK	X	OK	OK	OK

Granulac 230		65° wall angle				70° wall angle				75° wall angle			
		[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm
50g added	1. sample	X	X	B(20.0 g)	OK	X	B(13.0 g)	OK	OK	X	B(33.7 g)	OK	OK
	2. sample	X	B(2.1 g)	B(16.4 g)	OK	X	B(15.9 g)	OK	OK	X	B(27.0 g)	OK	OK
	3. sample	X	B(2.3 g)	OK	OK	X	B(13.8 g)	OK	OK	X	OK	OK	OK
	4. sample	X	B(2.1 g)	OK	OK	X	B(16.0 g)	OK	OK	X	B(19.9 g)	OK	OK
100g added	1. sample	X	B(2.0 g)	B(22.3 g)	OK	X	B(13.2 g)	OK	OK	X	B(37.2 g)	OK	OK
	2. sample	X	B(2.2 g)	OK	OK	X	B(7.0 g)	OK	OK	X	B(28.9 g)	OK	OK
	3. sample	X	X	OK	OK	X	X	OK	OK	X	B(43.4 g)	OK	OK
	4. sample	X	X	OK	OK	X	X	OK	OK	X	B(30.2 g)	OK	OK
150g added	1. sample	X	B(2.0 g)	OK	OK	X	X	OK	OK	X	OK	OK	OK
	2. sample	X	X	OK	OK	X	B(3.1 g)	OK	OK	X	B(110.1 g)	OK	OK
	3. sample	X	B(2.3 g)	OK	OK	X	B(28.0 g)	OK	OK	X	B(74.2 g)	OK	OK
	4. sample	X	B(2.1 g)	OK	OK	X	B(23.5 g)	OK	OK	X	B(128.5 g)	OK	OK

Wood flour		65° wall angle				70° wall angle				75° wall angle			
		[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm	[5]-[5] mm	[10]-[10] mm	[15]-[15] mm	[20]-[20] mm
50g added	1. sample	X	B(1.0 g)	B(3.8 g)	B(15.6 g)	X	B(3.0 g)	B(10.1 g)	B(23.4 g)	X	B(2.4 g)	B(14.0 g)	OK
	2. sample	X	B(1.0 g)	B(5.5 g)	OK	X	B(3.7 g)	B(5.8 g)	OK	X	B(4.7 g)	B(9.0 g)	OK
	3. sample	X	B(1.5 g)	B(6.4 g)	OK	X	B(3.8 g)	B(5.9 g)	B(21.8 g)	X	B(1.9 g)	B(14.0 g)	OK
	4. sample	X	B(2.1 g)	B(6.6 g)	B(15.0 g)	X	B(3.1 g)	B(4.7 g)	B(19.4 g)	X	B(2.4 g)	B(14.0 g)	B(29.0 g)
100g added	1. sample	X	B(1.0 g)	B(7.2 g)	B(14.0 g)	X	B(2.5 g)	B(6.8 g)	B(45.9 g)	X	B(3.3 g)	B(10.0 g)	B(50.0 g)
	2. sample	X	X	B(6.8 g)	B(46.5 g)	X	B(4.5 g)	B(3.6 g)	B(23.0 g)	X	B(2.2 g)	B(8.0 g)	B(49.0 g)
	3. sample	X	B(1.0 g)	B(5.5 g)	B(18.2 g)	X	B(2.0 g)	B(4.1 g)	B(45.5 g)	X	B(2.7 g)	B(17.0 g)	B(28.0 g)
	4. sample	X	B(1.0 g)	B(15.6 g)	B(15.0 g)	X	B(1.8 g)	B(3.1 g)	B(34.3 g)	X	B(2.7 g)	B(6.0 g)	B(24.0 g)
150g added	1. sample	X	B(1.2 g)	B(5.9 g)	B(18.5 g)	X	B(1.7 g)	B(8.2 g)	B(51.0 g)	X	B(1.5 g)	B(6.0 g)	B(29.0 g)
	2. sample	X	X	B(5.9 g)	B(21.7 g)	X	B(3.3 g)	B(9.6 g)	B(21.6 g)	X	B(1.8 g)	B(7.0 g)	B(40.0 g)
	3. sample	X	X	B(7.4 g)	B(9.5 g)	X	B(2.2 g)	B(9.5 g)	B(25.8 g)	X	B(1.6 g)	B(7.0 g)	OK
	4. sample	X	X	B(5.6 g)	B(8.9 g)	X	X	B(7.3 g)	B(27.0 g)	X	B(1.7 g)	B(10.0 g)	B(40.0 g)

expected angles associated, with transition of flow regimes [13,37], there is a slight trend of increased discharge with increasing wall angle. For the range of material mass loadings used, no significant trend in behaviour was seen.

Given the overall trend of flowability seen in the dataset, the flow function for each of the five materials was determined independently (Fig. 4) to confirm that the observed trend correlated with the community accepted standard measure of flowability. The measured flow functions confirmed the observed trend order in the dataset with Eskal 10 falling within the regime of free to easy flowing, Granulac 70 also free to easy flowing, Granulac 230 in the cohesive regime, Eskal 500 in the very cohesive regime, and wood flour also very cohesive.

Within the context of the current paper of reduced particle density regolith simulants, the particle density of the materials varies as given in Table 4, with Eskal 10 and 500 having particle densities of similar order of magnitude to lunar regolith, Granulac 70 and 230, reduced by approximately 50 % and wood flour by approximately 75 %. The latter being proxy for a reduced density lunar regolith simulant (in this case, one quarter rather than one-sixth of native lunar regolith particle density). Therefore, of the five materials, Eskal 10 and 500 can be viewed as proxies of the current community approach to using lunar regolith simulants – i.e. a simulant with similar particle density to lunar regolith and used in Earth gravity to observe materials handling behaviour. Therefore, the observed materials handling behaviour is expected to be different from that seen on the lunar surface in lunar gravity given the differences between Earth and lunar gravities and the effect on particle self-weight and consolidation stress. The significantly reduced particle density wood flour material, when used in Earth gravity as a proxy for a reduced particle density lunar regolith simulant, would have a self-weight and resultant consolidation stress approaching that of lunar regolith in lunar gravity and, therefore could be expected to exhibit similar materials handling behaviour if other materials features allow. This latter point is important as other materials properties, such as interparticle forces and particle geometry, can also have major contributions to materials handling behavior. These combined features are at the core of the use of the flow function concept as this combines such

contributions into a practical measurement that can predict overall behaviour [14].

Therefore, Eskal 10 and Granulac 70 have almost identical flow functions (note that flow function is independent of gravity as the consolidation stresses applied in testing are much higher than particle self-weight in the shear test). They are seen as easy to free flowing and therefore assumed that the contribution of interparticle forces and interlocking particle geometries is low and any change in consolidation stress due to particle density will be significant in influencing materials handling behaviour. Comparing the two “easy-flowing” materials in the hopper dataset shows that Eskal 10 discharges much more easily than Granulac 70 even though the flow functions are nearly identical; given the self-weight of Eskal 10 is double that of Granulac 70, this would explain this difference in behaviour, consistent with the predictions of the Jenike equation, the Bond number considerations and the DEM simulation. Therefore, this indicates that a reduced particle density simulant can exhibit different behaviour in 1g when the flow function of the normal and reduced density simulant is identical.

Eskal 500 and wood flour have very similar flow functions although wood flour has a marginally lower (more cohesive) flow function than Eskal 500. Both are viewed as having very cohesive behaviour – combination of high interparticle forces and interlocking particle geometries. The hopper dataset shows that Eskal 500 discharges significantly more easily than wood flour. Again, the difference in the self-weight between Eskal 500 and wood flour, a 3.7-fold difference, can be seen as a likely explanation of the difference in flow behaviour.

The Granulac 230 material was included as it enabled confirmation of the expected hopper discharge behaviour of materials with identical particle densities but different flow functions due to particle size. The behaviour observed in the hopper dataset agreed with the measured flow functions, the larger particles being easier to discharge.

After performing the flow property analysis (including the angle of internal friction, flow function, angle of wall friction and bulk density measurements) and then applying Jenike’s method of silo designing to get minimum arching dimension/hopper half angle, the results were compared against hopper breadboard results on the tested materials. The results from the hopper breadboard relates well with Jenike’s method of silo design elucidating that for a reliable mass flow in a wedge shape hopper, minimum arching dimension required will be 40 mm (correlating with the maximum slit opening for the hopper breadboard presented in Table 5) and hopper half angle would be around 18° (for worst case material i.e. wood flour). The main significance of the silo design testing was not only to avoid arching (material hang-up) or rat holing (material sticking around the walls) but also validating Jenike’s method of silo design.

Additionally, the laboratory hopper breadboard results strongly indicate that a change in particle self-weight can influence the materials handling behaviour, between materials with very similar flow properties. Thus, the use of reduced particle density lunar regolith simulants can be expected to more closely replicate lunar gravity handling of lunar regolith when used in Earth gravity than the existing common community use of normal density regolith simulants. By contrast, the use of simulants with lunar density in Earth gravity will give an over-optimistic picture of material flow, for materials that have any measurable cohesion (i.e. not completely free flowing).

9. Conclusions and future work

This work has strengthened the view that the current lunar community norm of using normal density lunar regolith simulants in Earth gravity is a poor predictor of future technology use on the lunar surface where lunar bulk materials handling is involved. Therefore, this paper introduces the pragmatic concept of using lunar regolith simulants with reduced particle density so that the material self-weight in Earth gravity is equivalent to the self-weight of normal lunar regolith in lunar gravity. As part of this, the requirements for such reduced particle density

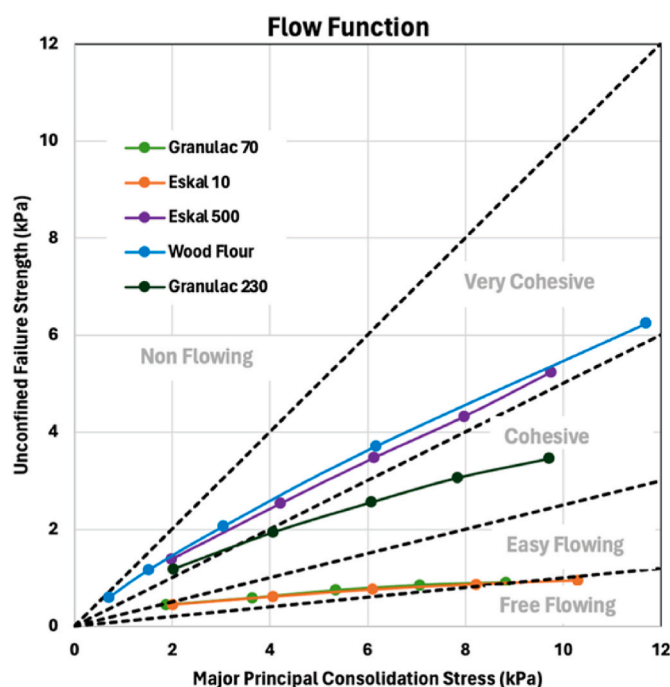


Fig. 4. Measured flow functions of the five materials used determined with Brookfield Powder Flow Tester (PFT). The dashed black lines delimit the different flow regimes and levels of cohesion [12].

simulants have been considered. Preliminary work has then explored this concept from a variety of differing viewpoints sufficient to justify further studies. Consideration of basic materials handling knowledge, both practical and theoretical, simulation via Discrete Element Method, and physical studies with a laboratory discharge hopper have been performed. For the latter physical studies, materials with reduced particle density have been identified for initial studies.

The conclusion of the studies of the effect of material self-weight is that there is expected to be an observable difference in practical material handling behaviour between using normal density and reduced density regolith simulants in Earth gravity. Furthermore, that reduced density regolith simulants in Earth gravity would be expected to behave closer to lunar regolith in lunar gravity than normal density regolith simulants in Earth gravity. Therefore, it is recommended that the community pursue this concept further.

It is recommended that the following are pursued. Firstly, more appropriate materials as candidates for reduced particle density simulants that fulfil the proposed requirements are identified. Secondly, the proposed requirements for reduced particle density simulants are refined further. Thirdly, further studies are performed to strengthen the arguments for the use of such simulants and to develop use cases. This could involve further theoretical, simulation and physical studies. It is anticipated that such activities could eventually lead to the development of lunar technologies with reduced risk of sub-optimal performance or even early failures due to problems with lunar bulk materials handling.

CRedit authorship contribution statement

Marko Pratnekar: Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vivek Garg:** Writing – review & editing, Validation, Resources, Formal analysis, Data curation, Conceptualization. **Baldeep Kaur:** Writing – review & editing, Resources, Data curation, Conceptualization. **Michael S.A. Bradley:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **David C. Cullen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Proposal of a new category of lunar regolith simulants: reduced particle-density simulants that exhibit equivalent self-weight in Earth gravity to native regolith in lunar gravity

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