Scale and water effects on the friction angles of two granular soils with different roughness

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A B S T R A C T

An integrated experimental study is presented which aims at relating the frictional properties at the particle scale to the bulk mechanical behavior for two different types of sands. We performed direct shear tests and inter-particle tests on lunar regolith simulant DNA-1A and Ottawa sand (benchmark material) under both dry and wet conditions. We found higher macroscopic friction angles for the lunar simulant in both dry and wet conditions, a smaller strength decay for Ottawa sand during reversal direct shear tests and similar strength envelopes of both materials under wet and dry conditions. Particle-scale tests evidenced higher inter-particle friction for DNA-1A in wet conditions with respect to the dry case for normal force lower than 2–3 N. For the lunar simulant, the differences between bulk and inter-particle friction appeared to be emphasized in dry condition and an evident effect of water on the friction coefficient was found only at the micro-scale.

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1. Introduction

The micromechanics-based prediction of phenomena occurring in granular assemblies is one of the most promising fields of engineering and physics. This way has been pursued, for example, to model localization processes [1] and the distribution of displacements and stresses in packing of spheres retained by wall [2,3]. Micromechanical approaches have been followed also for cohesive particle systems [4] and the rheology of a sheared suspension [5]. Studies concerning the micro- and multi-scale behavior of soils, based on both experimental, analytical and numerical studies, have also received significant attention in recent years by the geomechanics research community [6–15]. This is probably due to the relevance for geotechnical problems of the scales pertaining to the soil particle sizes (micro-scale) and the soil specimen sizes (macro-scale). With a more general approach, some researchers have attempted to solve the problem of scaling material properties for whatever scale, i.e., from the nanoscale to the macroscale [16]. When scaling the strength, it should be considered that the real, that is, size-independent, physical property is represented by the constant of proportionality (“fractal strength”; [17]). This problem has been traditionally approached by mechanics, but approaches purely based on geometry have also been proposed, in which the scaling laws are connected to the geometrical and multiscale character of the energy exchange domain [17]. Less general, although more affordable from an experimental point of view, is to determine a relationship between the property values pertaining to two given scales. For example, the need of identifying relationships between micro- and macro-soil properties, i.e., determined at the particle scale and the element volume scale, arises from the growing adoption of multiscale numerical simulations for solving boundary value problems [18]. Numerical simulations using the discrete element method have also shown a strong dependency of the macro-scale behavior of soils including both strength and volumetric behavior, on the grain-scale properties such as the interparticle coefficient of friction [12]. Experimental integrated studies on composite granular materials have also shown a straightforward correlation between macro-scale (bulk) critical state strength with the interparticle coefficient of friction, based on triaxial shearing tests combined with particle-scale tribological studies [9].

The effect of scale in tribological testing has been recently investigated by [19]. Although the measurement of microscopic properties by micromechanical tests [8,20–22] is mainly addressed in DEM calibration [10,23], these properties could also contribute to FEM modeling, for example when DEM results obtained by numerical scaling procedures,
as often needed for solving real size boundary value problems, must be compared with Finite Element simulations, to get more confident predictions [3]. In this case, for consistency, the FEM model should also be calibrated using micro-macro relationships for the mechanical parameters to be implemented.

Particle contact models very often assume the soil particles as regular spheres or disks [24], although in the last years more efforts have been made to take into account the irregularities of the particles [25–27]. In this respect, the experimental evidence must be strengthened to assist the theoretical and numerical modeling. At present day, it is particularly important to identify relationships between microscopic and macroscopic mechanical properties for the lunar regolith, and therefore for a lunar soil simulant, because this soil will be involved in complex geotechnical and structural design [28–33]. The reliability of numerical simulations for predicting the behavior of soils in interaction with geotechnical structures on the Moon (18,34) should be more enhanced to assist the theoretical and numerical modeling. At present day, it is particularly important to identify relationships between microscopic and macroscopic mechanical properties for the lunar regolith, and therefore for a lunar soil simulant, because this soil will be involved in complex geotechnical and structural design [28–33]. The reliability of numerical simulations for predicting the behavior of soils in interaction with geotechnical structures on the Moon (18,34) should be more enhanced to assist the theoretical and numerical modeling. At present day, it is particularly important to identify relationships between microscopic and macroscopic mechanical properties for the lunar regolith, and therefore for a lunar soil simulant, because this soil will be involved in complex geotechnical and structural design [28–33]. The reliability of numerical simulations for predicting the behavior of soils in interaction with geotechnical structures on the Moon (18,34) should be more enhanced to assist the theoretical and numerical modeling. At present day, it is particularly important to identify relationships between microscopic and macroscopic mechanical properties for the lunar regolith, and therefore for a lunar soil simulant, because this soil will be involved in complex geotechnical and structural design [28–33]. The reliability of numerical simulations for predicting the behavior of soils in interaction with geotechnical structures on the Moon (18,34) should be more enhanced to assist the theoretical and numerical modeling. At present day, it is particularly important to identify relationships between microscopic and macroscopic mechanical properties for the lunar regolith, and therefore for a lunar soil simulant, because this soil will be involved in complex geotechnical and structural design [28–33].

It is expected that the friction coefficient is characterized by different values depending on whether it is measured, at the grain scale (microscopic property) or the grain assembly scale (macroscopic property). In general, the mobilized friction angle can be expressed as: \( \phi_{\text{moh}} = \phi'_{i} + \phi'_{a} + \phi'_{b} \) [36], where \( \phi'_{i} \) is the inter-particle friction angle, \( \phi'_{a} \) is the resistance related to dilation (or particle climbing) and \( \phi'_{b} \) is the resistance mobilized by particle rearrangement (rolling and breakage). At the critical state, that is, with null dilation, \( \phi'_{cs} = \phi_{mu} + \phi_{b} \). The inter-particle friction angle mainly depends on the particle surface roughness and shape characteristics [12,15,22,37]–[38].

Taking into account these important considerations in multi-scale geomechanics and the characterization of lunar regolith, this research work presents an experimental study on the mechanical properties of the lunar simulant DNA-1A [28,29], based on multi-scale studies, and the results are compared with that of Ottawa sand, which is quartz-type soil used as benchmark in the study. The present study is part of a three-step research program which started with the mechanical characterization of the dry materials [28,30], and will finally investigate the implications of the multiscale modeling in terms of numerical simulation of the soil packing behavior. Here, results from new experiments enhanced with data from the studies by [28,30] are shown and discussed with the aim of comparing the differences between inter-particle and macroscopic friction angles of the two materials and relating these differences, on a qualitative standpoint, for both soils, to the particle morphological features and the humidity conditions. Additional data published in the literature on glass beads (multi-scale test results) are recalled, based on the study by [9], so as to compare the results from the lunar regolith, which material has very irregularly-shaped and very rough grains with that of two benchmark materials; both benchmark materials have very high consistency of their surface morphological features, but one of them is an “engineered soil” (glass beads), while the second one is a natural soil (Ottawa sand). The findings from the study will give evidence of how the grain characteristics control the strength at the macro-scale.

2. Materials and testing procedures

2.1. Compositional and morphological complexity of the materials

The grain size distribution and the chemical composition of the studied materials are shown in Fig. 1 and Fig. 2, respectively, as resulting from previous studies [28,30]. The mean grain size of Ottawa sand is around 4–5 times larger than that of the lunar regolith. Moreover, a wider range of particle sizes characterizes the lunar simulant with respect to Ottawa sand, as DNA-1A consists of a grinded volcanic material, whereas Ottawa sand is a uniform naturally occurred soil.

Marzulli and Cafaro [28] also investigated the dominant shapes of the DNA-1A particles by SEM and recognized two main grain textural types:

1. Clast with vesicles of irregular shape probably associated to gas in the magma;
2. Fragments of juvenile material rich in crystal and minerals, sometimes with small particles attached to each other.

The roughness of the grains was quantified in terms of the root mean square (RMS) roughness denoted as \( S_{\text{rms}} \) from Eq. (1), using an interferometer (Veeco NT9300 optical surface profiler).

\[
S_{\text{rms}} = \sqrt[2]{\frac{1}{u} \sum_{i=1}^{u} (W_i^2)}
\]

where \( u \) is the number of measured data points and \( W = \) the elevation relative to the base surface.

In Fig. 3, flattened surface profiles of both materials are reported. The average roughness of DNA-1A was found to be equal to 1476 (±379) nm, which is much higher than that of Ottawa sand (equal to 204 ± 42 nm) based on the analysis on a set of grains from both materials by [30]. To further explore the morphological features of the two materials, additional SEM analyses have been performed (Fig. 4). The ZEISS VP SIGMA 300 scanning electron microscope, equipped with detector OXFORD X-MAX 20 for the chemical micro-analyses, has been employed.

The roughness of the surface of the two materials is detectable at different scales. At a magnification of 100 times (Fig. 4a), the Ottawa sand can be recognized to be fundamentally smooth: the macroscopic irregularities shown in Fig. 4b, pertaining a grain of Ottawa sand, have thicknesses in the order of tens of microns. The particles of DNA-1A are quite irregular in shape (Fig. 4c and d) and the dominant morphological types previously observed by [28] for this lunar simulant can also be found in the fraction smaller than 75 \( \mu \)m (Fig. 4c). Table 1 reports chemical spectra of Ottawa sand deduced on both localized (i.e. spectra 1 and 2; Fig. 5) and wider zone of a grain (i.e. spectra 3 and 4; Fig. 5): although the punctual analyses may reveal differences, from a chemical point of view the grain surface can be considered to be basically homogeneous.

In Fig. 6a, the variation of chemical composition of a 200–300 \( \mu \)m grain of DNA-1A along a scanning line is shown. The core of the grain and the asperity seem to have similar composition, whereas in the middle portion a sharp decrease in Si, Al and K, corresponding to a local increase in Fe, is detected. Fig. 6b, pertaining to another grain of lunar simulant, of similar size, confirms that the heterogeneity of the chemical composition at the grain scale is quite random and not specifically reflected in a grain zonation. On the basis of this observation, it seems that the grain asperities do not necessarily represent weaker zones, i.e. zones prone to rupture, with respect to other portions of the grain. Therefore, their breakage and the related debris formation under inter-particle compression and shearing tests, observed and invoked by Sandeep et al. [30] to justify the strength decay with loading cycles, should be associated to high local stress concentration at the contact asperities.

Since Ottawa sand is fundamentally homogeneous, as discussed before, and the compositional heterogeneity of the DNA-1A particles is not specifically due to their surface and asperities, the differences in the mechanical response of the two materials can be related to their overall chemical and mineralogical compositions as well as their roughness.

The presence of damaged particles in the investigated lunar simulant is expected since the natural material was grinded to obtain a target granulometry, i.e. in the range of the grain size distribution of the original lunar soil, and high interparticle stresses probably developed. In Fig. 7, a particle made of SiO2, of about ten microns, with a clear fracture system is shown. The visible fracture opening seems to be of the order of...
tens of nanometers. It is plausible that other fractured particles and crystals are present in the material and that micro- and nano-fractures represent a predisposing factor for the material damaging at the macro-scale.

2.2. Experimental program and testing procedures

Mechanical tests have been carried out for the two materials, both on element volume and at the particle scale. For the first type of tests, direct shear tests [39] have been carried out using a Casagrande shear box on self-weight compacted specimens, of 6 cm × 6 cm square section, both dry and submerged. These experiments were performed in a displacement-controlled mode with a rate of 0.05 mm/min.

For the second type of tests, the inter-particle loading apparatus (Fig. 8) designed by Senetakis and Coop [20] and Nardelli and Coop [22] and housed at the City University of Hong Kong was used. The apparatus consists of three loading arms in three orthogonal directions. Each arm is equipped with a stepping motor, a load cell (100 N capacity) and a non-contact eddy current displacement sensor (10⁻⁵ mm resolution). Before the loading tests, the pair of grains is selected and they are glued to the top and the bottom brass mounts. Normal force is applied at the grain contacts by lowering the top grain on to the bottom grain and the shearing tests are conducted by moving the bottom grain while the top one is stationary in the horizontal direction, maintaining, during shearing, a constant normal load. The particle-scale tests have been carried out in different humidity conditions and are summarized in Table 2.

Based on DEM simulations, [23] reported that the inter-particle forces at the soil grain contacts may reach maximum values of the order of 4-5 N, for typical pressures of geotechnical-geological engineering problems. This corresponds to the maximum normal forces applied in the present study. The total confining stresses at which the direct shear tests have been carried are low to medium. The corresponding intergranular normal forces should be calculated with theoretical assumptions on the coordination number and the void ratio [40]. By approximate calculations based on data from Lambe-Whitman [41], it seems that in the direct shear tests the intergranular stresses might be

![Fig. 1. Particle-size distribution of DNA-1A and Ottawa sand.](image1)

![Fig. 2. Chemical composition of DNA-1A (Marzulli & Cafaro, 2019) and Ottawa sand (Sandeep et al., 2019).](image2)
lower than in the micromechanical tests. However, within the soil specimen, the stress distribution during shearing is highly non-uniform and, locally, the intergranular stresses could be very high, depending on the particles interlocking. The magnitude and stress distribution of the stresses would be expected also to be affected by the morphology of the grains, as the locality of particle shape in the vicinity of the contacts may influence the particle-scale contact response [42–43].

The microscopic parameters have been deduced on a selected class of grain sizes, for experimental needs [30]. Although the complete characterization of the material would require mechanical tests on all size classes and calculation of further shape parameters [44–46], the results of the present study will allow to generalize the interpretations. From now on, abbreviations will be used to indicate Ottawa sand and lunar regolith simulant, namely OS and DNA-1A, respectively.
2.3. Micro-hardness and stiffness of the grains

The different chemical and mineralogical compositions of the two materials are reflected in the different hardness of their grains and particles. Additionally, micro-hardness tests were also conducted in a force-controlled mode at different normal forces (0.2, 0.5 and 1 N) using the Fischer-scope HM2000 micro-hardness tester. Figs. 9 and 10 show a comparison of the micro-hardness and Young's modulus values obtained from micro-hardness tests for both material types. Indeed, differences have been detected in terms of micro-hardness (Fig. 9): 0.32 (±0.11) GPa for DNA-1A and 5.8 (±0.90) GPa for Ottawa sand [30]. In Fig. 10, Young modulus values for the two materials are shown, which suggest that, at the grain scale, Ottawa sand is one order of magnitude stiffer than DNA-1A.

3. Materials shear strength: experimental results

3.1. Element testing results

Results of direct shear tests carried out on both DNA-1A and OS at low to medium normal stresses (< 100 kPa), both in dry and wet conditions, are shown and discussed in this section. Multiple reversal direct shear tests have also been performed on both dry materials at higher confining pressures to determine the shear strength decay at the interface of the two half-boxes. Most of the data pertaining to DNA-1A in dry conditions have already been shown and discussed previously by [28]; they are here reported in order to enable a comparative analysis of the experimental data of the two materials.

3.1.1. Direct shear tests in dry conditions

Fig. 11 (a,b) shows the tangential force versus horizontal displacement during direct shear tests on dry DNA-1A and dry OS. For both sands showed hardening response, as expected for loose uncompacted materials. In few tests, a sudden decay of strength can be observed, after which the material is recovering strength and the previous trend.

To explain this behavior, which seems to follow a stick-slip mode [17], several tests should be repeated for the same experimental conditions to exclude technical testing problems.

Fig. 11 (c,d) shows results of vertical versus horizontal displacement during direct shear tests on dry DNA-1A and dry OS. For DNA-1A (Fig. 11c), as already thoroughly discussed in [28], a transition from dilative to contractive behavior can be detected at a normal confining stress of about 10 kPa. Differently, Fig. 11d shows that OS exhibits a contractive behavior only beyond 90 kPa. Moreover, the dilation of DNA-1A is one order of magnitude lower than that of OS.

OS was found to possess lower shear strength than DNA-1A. Fig. 12 shows the shear stress versus normal stress at failure, i.e. at the maximum of the shear force, corresponding in this case to critical state ($\phi'_{\text{bulk}} = \phi'_{\text{cs}}$) due to the absence of softening, for both dry OS and DNA-1A. In the figure, the regression line (failure envelope) obtained by interpolating all data set and imposing zero intercept is reported. Despite the high correlation, it is seen that all data points at low stresses are located above the envelope. Marzulli and Cafaro [28] related this observation to the transition from dilative to contractive behavior.

Rousé [47] investigated the stress dependency of the critical state friction angle at low stresses for seven different sands in direct shear and also examined the relative role of grain shape: they reported that the more rounded the sand particles the smaller the drop in $\phi'_{\text{cs}}$ for normal stresses between 4 kPa and 50 kPa. For this reason, in Table 3 two different bulk friction angles for each material in dry conditions are reported, one pertaining to vertical stresses approximately in the interval 9÷21 kPa (see “low stresses range” in the Table), the other one calculated over higher vertical stresses (see “medium-higher stresses range” in the Table). By adopting a linear regression, angles of 47.9° and 40.8° for DNA-1A and of 45.0° and 36.5° for OS can be deduced, respectively (Table 3). Based on triaxial tests on self-weight compacted dry specimens of DNA-1A, Marzulli and Cafaro [28] found a peak friction angle of about 49°. They also measured a repose angle for the material when cone-shaped around 40°, confirming the high friction of the lunar regolith.

3.1.2. Direct shear tests in submerged conditions

The comparative analysis of the soil shear response under dry and wet conditions has been carried out by performing tests on fully saturated specimens at normal stresses up to about 31 kPa; higher stress values would be, in general, of little engineering interest for a lunar simulant. Fig. 13 (a,b) shows plots of tangential force versus horizontal displacement and vertical displacement versus horizontal displacement during direct shear tests on wet DNA-1A and wet OS. Despite some evidence of dilation under shearing, especially for OS (Fig. 13b), the curves in Fig. 13a exhibit hardening or only slight softening. Fig. 14 shows the
shear stress versus normal stress at failure (i.e. at the maximum of the shear force) for both wet materials. By linear interpolation within the investigated range (i.e. approximately 11÷31 kPa), bulk friction angles of about 41° and 46° are calculated for OS and DNA-1A, respectively. For DNA-1A, the value appears to be only slightly lower than that measured under dry condition within the low stresses range, whereas for OS the discrepancy seems to be more important (Table 3).

3.1.3. Decay of the interface friction

Fig. 15 shows the evolution of the maximum tangential force with repeated runs, during reversal direct shear tests on dry DNA-1A (97 kPa), dry DNA-1A (356 kPa) and dry OS (97 kPa).

For the test “97 kPa DNA-1A”, an increase in shear strength from the first to the second run can be observed, probably due to the densification of the specimen and increased interlocking, but generally a progressive reduction in the maximum shear force with the repeated runs is detected, especially beyond the second to third cycle, for both materials. The progressive decay of the friction at the interface (sliding surface in between the two half-boxes) can be attributed to both isoorientation of non-spherical particles along the shear direction and breakage of the weaker particle asperities for which the indentation was strong. The asperities should contribute the momentum transmission during shearing and, therefore, the particle rolling or, where the interlocking is strong, their breakage.

The data pertaining to the first three runs suggest that for OS the decay is smaller than for DNA-1A. This is plausibly due to the different particle shapes, for two reasons: the higher sphericity of the OS grains makes the material less prone to isoorientation, with respect to the lunar simulant, and the higher roughness of the latter should involve more important breakage and rolling phenomena during the reversal tests, as discussed before. These phenomena seem to be emphasized at higher normal stresses since the decay for DNA-1A was found to be faster at 356 kPa than for 97 kPa vertical stress (Fig. 15). Based on the test performed at 356 kPa, DNA-1A seems to possess a residual friction angle, \( \phi_r \), of about 34°, whereas the test at 97 kPa on DNA-1A gave a not plausible strength decay after a few runs, probably due to loss of material along the shear plane. For OS the difference between critical state and residual friction angles is very low, as generally expected for sands, particularly for sands with spherical grains.

3.2. Grain contact behavior

As previously mentioned, tests have been performed on both granular materials (Table 2) and grains have been tested in four different conditions:

1) Dry (data after Sandeep et al. [30]).
2) Immersed in water and tested (Code: DNA-1A-I).

Fig. 6. Variation of chemical composition across two DNA-1A grains (a; b).

Fig. 7. Fractures system across a particle of lunar simulant.
Representative shearing test results on the DNA-1A grains under different environmental conditions are shown in Fig. 18. Similar to tests on dry DNA-1A granules [30], for different immersion conditions the tangential force increased non-linearly with the increase in displacement after which steady-state/micro-slip condition was reached. Representative curves showing tangential stiffness degradation with the increase in tangential displacement are presented in Fig. 19. From the stiffness degradation curves, it is evident that the environmental conditions did not produce any notable changes in the stiffness degradation response of the DNA-1A granules.

The variation of the inter-particle friction for the tested DNA-1A grain pairs under different environmental conditions is presented in Fig. 20. Within the scatter of the data, the tests conducted in the presence of water have relatively high values of inter-particle friction when sheared at low values of normal force (1–2 N). Sandeep et al. [30] reported a maximum inter-particle friction of 0.5 for DNA-1A grains tested in dry condition. In all the other conditions at 1 and 2 N normal force friction values up to 0.7 are observed. However, from 3 and 5 N of normal force the inter-particle friction values are similar in all the different testing conditions (Fig. 20). These micromechanical features will be discussed in the next section.

4. Scale and water effects on the friction angles

4.1. Friction in dry conditions

Table 3 reports the bulk and contact friction angles of the studied materials. The roundness values of the grains presented in Table 3 are based on visual comparison of grain shapes with Krumbein and Sloss chart [49]. Among the friction values reported in Table 2, in order to compare macroscopic and microscopic friction angles, only the data concerning the 1 N normal contact force have been averaged. It should be noted that OS has almost the same \( \phi' \) as that of glass beads (GB) in Table 3, whereas the macroscopic friction angles are substantially different. This observation can be explained by invoking the parameters in Table 3 and, due to the morphological simplicity of the two materials, allows us to draw some conclusions of general value. Indeed, the roughness values of OS and GB are very similar and the measured inter-

<table>
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<th>Code</th>
<th>Normal force (N)</th>
<th>Steady state (nominal) tangential force (N)</th>
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particle friction angles are too, consistently, because at the grain scale, keeping other parameters equal, increase in roughness will increase the inter-particle friction [37]. It should also be considered that the bulk strength of granular materials is contributed, in addition to the crushability of the grains, by both the inter-particle friction and the resistance to rotation, the latter component being linked to the particle shape [9,12,36,50]. OS is only little less rounded than GB (Table 3); nonetheless, the effect on the resistance to rotation and then on the bulk strength appears to be relevant. Therefore, since roughness should contribute to mechanical macro-effects almost equally for the two materials and their differences in roughness and roundness are both small, roundness seems to affect the bulk strength more strongly.

DNA-1A and OS, instead, differ markedly from each other. The lunar simulant is much rougher and much more angular than OS, so that marked difference can be observed in both the inter-particle friction and the bulk strength. Therefore, when comparing these two materials, only the combined effect of roughness and particle shape (i.e. coupling of sliding and rolling resistance) can be taken into account. In this case, however, approximate value of $\phi_b'$ can be back-calculated [9], by measuring $\phi_b'$ in the laboratory.

Under dry conditions, the two soils exhibit different $\phi_b'$. Moreover, based on the difference between $\phi_{cs}'$ and $\phi_{r}'$, DNA-1A appears to be much more prone to particle damage or fabric changes compared with OS; higher structural damage at the particle scale, that is, decay of $\phi_{r}'$, was also found for the same material as shown in Fig. 17. Moreover,

**Fig. 9.** Probability vs Micro-Hardness for a) DNA-1A and b) Ottawa sand.

**Fig. 10.** Probability vs Young Modulus for a) DNA-1A and b) Ottawa sand.
Fig. 11. Tangential force versus horizontal displacement during shear tests on (a) dry DNA-1A (Marzulli & Cafaro, 2019; new: 97 kPa test) and (b) dry Ottawa sand; vertical versus horizontal displacement during the same tests on (c) dry DNA-1A (Marzulli & Cafaro, 2019; new: 97 kPa test) and (d) dry Ottawa sand.

Fig. 12. Shear stress versus normal stress at failure for DNA-1A and Ottawa sand in dry conditions.

Table 3
Morphological and friction parameters for the studied materials (the inter-particle friction angle is assessed based only on tests carried out at 1 N normal contact force).

<table>
<thead>
<tr>
<th>Material</th>
<th>Particle size (for microtest)</th>
<th>Hardness</th>
<th>Roundness</th>
<th>Roughness</th>
<th>$\phi_{\text{bulk}}$ Low stresses range</th>
<th>$\phi_{\text{bulk}}$ Medium-higher stresses range</th>
<th>$\phi_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNA-1A dry</td>
<td>1.0–1.8 mm</td>
<td>0.3 GPa</td>
<td>0.6</td>
<td>1476 nm</td>
<td>47.9°</td>
<td>40.8°</td>
<td>21°</td>
</tr>
<tr>
<td>DNA-1A wet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OS dry</td>
<td>0.5–0.8 mm</td>
<td>5.8 GPa</td>
<td>0.8</td>
<td>204 nm</td>
<td>45.9°</td>
<td>36.5°</td>
<td>30°</td>
</tr>
<tr>
<td>OS wet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7.6°</td>
</tr>
<tr>
<td>Glass Beads (*)</td>
<td>0.3–0.6 mm</td>
<td>3.3 GPa</td>
<td>0.90</td>
<td>145 nm</td>
<td>24.0°(**)</td>
<td></td>
<td>7.4°</td>
</tr>
</tbody>
</table>

Data from [30].

Data from [8].

(*) Data from [9].

(•) Determined by triaxial tests performed at 50–400 kPa of isotropic consolidation effective stress.
the average micro-hardness value of DNA-1A is much lower than the hardness values of OS grains (around one order of magnitude), which also confirms that the DNA-1A grains are more prone to particle damage and fabric changes.

The relation between macroscopic and contact friction angles can also be interpreted in terms of the incidence of the kinematic "freedom" of the particles. Calvetti [51] reported results of 3D DEM simulations from Suiker and Fleck [52] and of 2D DEM simulations from Calvetti.
and Nova [53], showing relationships between macroscopic and contact friction angle for two different kinematic assumptions (i.e., particle free rotation and no rotation). The experimental data concerning DNA-1A, as measured in the present work, lie near the linear trend, pertaining to the no-rotation assumption, found by the abovementioned authors. This fact seems to be consistent with the morphological features of the lunar simulant particles, as observed by SEM (Fig. 4). Indeed, it is plausible that the high roughness of the DNA-1A particles increases their interlocking and then the kinematic assumption of "no rotation" seems to be consistent for this kind of material under virgin shearing. In contrast, repeated shearing cycles should induce abrasion and breakage of the asperities and, therefore, increase the kinematic freedom.

4.2. Friction in wet conditions

Evidence on the incidence of water, either submerging or condensed, on the inter-particle friction has been provided in the last decades. For quartz sand grains, as highlighted earlier, Senetakis et al. [6] and Nardelli and Coop [22] did not observe any noticeable effect of humidity on the inter-particle friction values. However, the material surface roughness can cause differences between dry and wet friction coefficient, as stated by Lambe-Whitman [40], who reported data from Bromwell [54] and Dickey [55] concerning quartz and showing that

Fig. 15. Maximum tangential force versus run number during reversal direct shear tests on dry DNA-1A (97 kPa, 356 kPa) and dry Ottawa sand (97 kPa).

Fig. 16. Normal load vs normal displacement for dry and immersed grains of DNA-1A.

Fig. 17. DNA-1A grain pair tested in submerged condition (a) before the micromechanical tests (b) during loading (c) after the loading. The dashed red circle shows the damage of asperities on the top grain after the micromechanical test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
the above-mentioned difference is the highest for smooth surfaces and diminishes for very rough surfaces.

The experimental data in Fig. 20 seem to indicate some influence of the water on the inter-particle friction. The inter-particle friction coefficient of the dry grains is lower than the one of the immersed grains for the same normal force up to 2 N. It seems that a threshold value of normal force, in between 2 and 3 N, can be postulated, beyond which the presence of water causes reduction of the inter-particle friction with respect to the dry condition. We can have a speculation on this. We could suppose that at low normal forces (1 and 2 N) the inter-particle dry friction coefficient is lower than the one detected for immersed grains because the breakage of asperities is not fully mobilized yet and the grain surface is characterized greatly by asperities, so that the overall area of contact between a pair of grains can be seen, at a different scale, as the result of several “micro-contact areas” [56].

Once the asperities damage becomes more pronounced, that is at higher inter-particle normal stress, the water lubrication of the “smoothed” grain surface becomes more effective. This interpretation, which requires observation of the wet grain surface at very high magnification to be corroborated, then involves a mechanical characterization of this kind of granular material by approaching three different scales: grain assembly scale (i.e. “element volume”), grain scale and asperity scale, pertaining different stress fields.

Summarizing, the difference between bulk and inter-particle friction angles appears to be emphasized in dry condition for the investigated lunar regolith simulant. Moreover, the effect of water on the friction seems to be evident only at the micro-scale for this simulant, especially for the lowest investigated normal contact forces, whereas on element testing this effect appears to be negligible. This is consistent with what was observed by Marzulli and Cafaro [28], who compared the one-dimensional compression curves of DNA-1A for both dry and submerged conditions and found practically the same compressibility. This could be explained by the saturation of the contact force distribution and the mean coordination number with respect to the microscopic friction coefficient [57,58]. Indeed, macroscopic stiffness and strength do not increase significantly when the microscopic coefficient increases above a certain value [12,59,60].

5. Conclusions

Results of an experimental multiscale study concerning the friction coefficients of the lunar simulant DNA-1A and Ottawa sand have been shown and discussed in this paper. Ottawa sand has been employed as a “benchmark material” due to its compositional homogeneity, high roundness and low roughness. The lunar simulant particles have been instead found to have higher compositional heterogeneity, particle angularity and surface roughness.

The direct shear tests carried out under both dry and submerged conditions revealed macroscopic friction angles much higher for the lunar simulant. Reversal direct shear tests suggest that for OS the
strength decay is smaller than that of DNA-1A and this difference has been related to the influence of grain shape. Also, for DNA-1A, the strength envelope deduced on wet specimens appears to be basically the same as that pertaining to the dry condition, at least for the investigated stress range.

Based on the micromechanical tests performed on DNA-1A, it seems that a threshold value of normal force, in between 2 and 3 N, can be delineated, beyond which the presence of water causes reduction of inter-particle friction with respect to the dry condition. Therefore, the effect of water on the friction coefficient seems to be evident only at the microscale for this material. The difference between bulk and inter-particle friction angles appears to be emphasized in dry condition for the investigated lunar regolith simulant. This aspect has important implications in the design of earthworks for the Moon surface, where dry conditions characterize the soil environment.

Finally, although the OS grains revealed a contact friction angle similar to that of glass beads, the macroscopic friction angle of OS is markedly higher than that of an assembly of glass beads. This fact has been explained in this work by the stronger influence of roundness, with respect to roughness, on the bulk strength.

Credit author statement

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.

Declaration of Competing Interest

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