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Does water lubrication affect friction differently for rocks and soils? Evidence and open questions

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Abstract: The present paper focuses on the shear strength exhibited by rocks and soils when sliding along dry and wet surfaces, with this mechanism of failure being strongly related to the water lubrication phenomenon. It is well known that the frictional behaviour of geomaterials requires multiscale investigation. Under this perspective, experimental evidence of both friction at the grain scale (i.e. interparticle friction) and friction along sliding surfaces of rock and granular soil samples (i.e. surface friction) are analysed by using data from the literature. The review is addressed at linking different scales, stating the differences between rocks and soils in terms of frictional response to sliding and trying to point out still open problems for the research.

Keywords: Water lubrication; friction scale; fractures; sliding; roughness.

1 Introduction

Interparticle and surface friction problems are solved by approaches coming from different scientific fields. Physics analyses fundamentals of the friction, geology and geophysics study the lubrication of faults, geotechnics looks at geomaterials for civil engineering and tribology focuses also on the response of materials for industrial applications. All these fields contribute each other to the knowledge concerning friction between particles and on surfaces and interfaces.

Relevant for geotechnics is the effect of water on the shear strength along already formed sliding surfaces within rocks and soils. Water affects the behaviour of fractured rocks in terms of failure and deformation in several engineering works (Jaeger et al. 2007). Numerous investigations have been carried out to quantify the effect of water on the mechanical properties of rocks (Lajtai et al. 1987; Ojo and Brook 1990; Dove 1995; Feng et al. 2001; Ning et al. 2003; Nara et al. 2010; Wasantha and Ranjith 2014; Cherblanc et al. 2016; Hua et al. 2016; Wong et al. 2016; Zhou et al. 2016; Qiao et al. 2017; Zhao et al. 2019).

It is worth nothing that water-induced degradation of the intact rock (or soil) and water lubrication are distinct problems. When a rock is immersed in a solution with high proportion of H^+ for a long period of time, chemical reactions can happen more efficiently, which result in more ductile and softer rock sample (Li et al. 2003; Ning et al. 2003). Water lubrication may affect the shear strength along fracture walls even in the absence of weakening of the material matrix. Past literature reports that under wet conditions, the friction angle of different rocks decreases (Gutierrez et al. 2000; Ulusay and Karakul 2016; Li et al. 2020). Experiments on marl fractures, for example, reveal that shear strength is intensely related to water content: fracture cohesion and friction angle drop from 0.41 to 0.32 MPa and from 22° to 12°, respectively, when moving from dry to saturated condition (Pellet et al. 2013). These mechanical changes should be justified, in principle, by providing evidence of the material weakening and the fracture lubrication effects separately.

Understanding the mechanisms governing the lubrication of soils can benefit from studies on the frictional response of powders and grains, not necessarily of geological origin, since for clayey soils, the mechanical effects of water are of very different nature and invoking lubrication contribution to friction is questionable. These studies often refer to relative motion along interparticle contact area and to the related frictional behaviour, sometimes investigated under different humidity conditions. For example, Karde and Ghoroi (2021) observed for a fine powder a decay of the stick-slip motion of the particles, under applied normal and shear stresses, with the increase in humidity, which causes a transition from stick-slip motion to steady sliding.

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Starting from this background, the present paper focuses on the shear strength exhibited by rocks and granular soils when sliding along dry and wet surfaces, aiming at relating their behaviour to the water lubrication phenomenon. To achieve this goal, different scales of analysis will be adopted. It is well known that the frictional behaviour of geomaterials requires multiscale investigation. For example, Diao and Espinosa-Marzal (2018) performed single-asperity friction experiments using an atomic force microscope with the aim of understanding the role of water in fault lubrication, by linking the tectonic scale to the nanoscale. In the following sections, experimental evidence of both the friction at the grain scale (i.e. interparticle friction) and the friction along sliding surfaces of rock and soil samples (i.e. surface friction) will be analysed from the literature. The review is addressed at linking different scales to deduce some general conclusions from a phenomenological point of view, stating the differences between rocks and soils in terms of response to water lubrication and trying to point out still open problems for the research.

2 A Tribological Premise: Role of the Surface Asperities

Defining friction requires the definition of a scale. This physical problem can be described with a microscopic approach, as a single atom strongly interacting with a rough surface displaced in a tangential direction (Kim and Suh 1991). When two adhering surfaces are moved across each other, even in the absence of a load, a finite force or energy must be exerted that goes into breaking the adhesive intermolecular bonds across the shearing interface (Israelachvili 2001). Friction can also be defined, looking at engineering aims, with reference to a finite body of given mass sliding on a plane (Coulomb 1776; Newmark 1965). However, although not always explicitly computed, the elementary physical factors governing the friction act at all scales. Indeed, the friction force is fundamentally affected by the normal load since this force dictates the number of atomic interactions (Rymuza and Pytko 2012). In this respect, attempts to define friction in a general way (for whatever scale) should be made, that is, introducing a size-independent strength (Carpinteri and Pugno 2005; Pugno 2007).

In the context of geomechanics, the shearing resistance along material surfaces is considered to arise from two components: the basic frictional resistance, that is, the inherent component pertaining to flat surfaces and determined by the material composition, and the resistance offered by the roughness on the surface, like for rock fracture surfaces (Barton 1971; Li et al. 2020).

In a tribological context, however, the friction coefficient is not seen as a material constant (Stribeck 1903). According to the Stribeck curve (Fig. 1; Prölß et al. 2018), for example, this coefficient develops with the rotational speed of journal bearings for industrial machinery. This curve distinguishes three different lubrication regimes: in the mixed lubrication regime, the external force is compensated by the hydrodynamic pressure p_{hyd} of the oil film and the solid contact pressure p_c of the asperities that are in contact. If the lubricant film thickness falls below a critical value h_{cr} (Fig. 1), surface roughness phenomena cannot be neglected, since the asperities can hinder or support the lubricant flow, depending on their orientation, and thus affect the hydrodynamic pressure buildup (Prölß et al. 2018). It is interesting to mention that according to Karde and Ghoroi (2021), who tested a humidity-conditioned fine powder, for a constant sliding velocity, the same transition of the Stribeck curve in terms of lubrication regimes can be detected when increasing Relative Humidity (RH). The physical reason is that the variation in friction coefficient becomes directly proportional to the fluid viscosity, which depends on fluid film thickness, where the film thickness and its nature (discrete or continuous) is, in turn, RH dependent.

Although the lubrication of machinery is not strictly equivalent to the lubrication of geomaterials and in geotechnical problems the relevance of the sliding velocity is sometimes questionable, the basic theoretical aspects are of general value: the surface asperities affect the water lubrication efficacy for geomaterials too, as it will be shown later.

It is worth noting that a velocity-dependent frictional behaviour is expected even for dry conditions, as found at the nanoscale by Diao and Espinosa-Marzal (2018), who detected this dependency on calcite for both wet and dry conditions. This fact implies that a comparative study on frictional response of surfaces and asperities under dry and wet conditions should be carried out for equal shearing rate to correctly interpret the differences in friction.

In the work mentioned above, Diao and Espinosa-Marzal focused on the frictional strength of single-asperity contact to provide a contribution to the understanding of the frictional strength of calcite-rich faults. They employed atomic force microscopy (AFM) by sliding an oxidised silicon tip along an atomically flat calcite plane, to measure the friction force as a function of the applied load and sliding velocity. The authors, based on

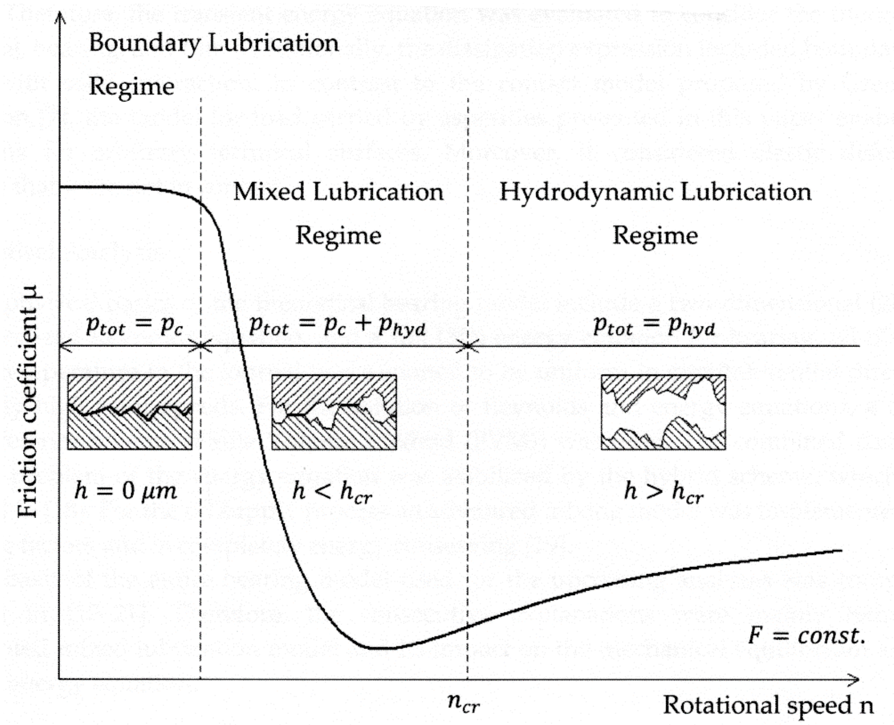

Figure 1: Stribeck curve with different lubrication regimes (after Prölß et al. 2018).

the measured frictional behaviour of calcite in aqueous solutions, distinguish three different mechanisms of energy dissipation (Fig. 2): viscous dissipation at low stresses (LS), shear-promoted thermally activated slip at intermediate stresses (IS) and pressure-solution facilitated slip at higher stresses (HS; Hertzian contact stresses $\sigma_n >$ 400 MPa). Specifically, Diao and Espinosa-Marzal provide evidence for the presence of a lubricating film composed of ions and water that remains confined between calcite and silica surfaces even under high applied stresses. In a previous work (Diao and Espinosa-Marzal, 2016), they showed that a strong repulsion between the confining surfaces is originated by colloidal forces between the two surfaces across the thin film of solution (a few nanometres thick), preventing the solution to be squeezed out under the applied pressure (Israelachvili and Pashley 1983; Røine et al. 2015). Diao and Espinosa-Marzal (2018) also found that pressure-induced dissolution of calcite in $CaCl_2$ solution at sufficiently high stresses and slow sliding velocities can significantly reduce friction, compared to dry conditions. At the sliding conditions at which the friction decreased, AFM imaging of the calcite surface showed the track of the tip, which instead was not observed when similar test was carried out in ethanol, where calcite is insoluble. The authors hypothesise that if calcite under AFM tip could be dissolved and rehydrated before the tip slides away, it would facilitate slip.

The interesting effect of the slip rate on the friction behaviour found by Diao and Espinosa-Marzal (2018) reveals that the kinetics of pressure solution plays an important role in the lubrication process. Figure 3, pertaining to tests carried out in $CaCl_2$ solutions at 0.2 μm/s sliding velocity, shows that friction decreases with increasing load in the HS regime (change from green to red in the figure). At higher velocity (2 μm/s) and for similar aqueous environment, the authors did not find the same behaviour, confirming the importance of the kinetics of pressure-induced calcite dissolution, which can facilitate slip, provided that the time for the chemical reaction is long enough. Consistently, in the absence of aqueous solution, the friction force was found to increase monotonically with the applied load at all sliding velocities. Remarkably, Diao and Espinosa-Marzal found that pressure solution is enhanced with increasing normal stresses, requiring less time for dissolution.

Another crucial factor controlling the water lubrication efficacy is the presence of impurities on a surface, either flat or rough. Impurities can have different origins and can be, for example, debris resulting from asperities' abrasion or a thin film of organic matter. In Table 1, values of the friction coefficient for some minerals under both dry and saturated conditions are shown. The data (Horn and Deere 1962) pertain to samples with accurately flattened surfaces and give evidence of a different frictional response to

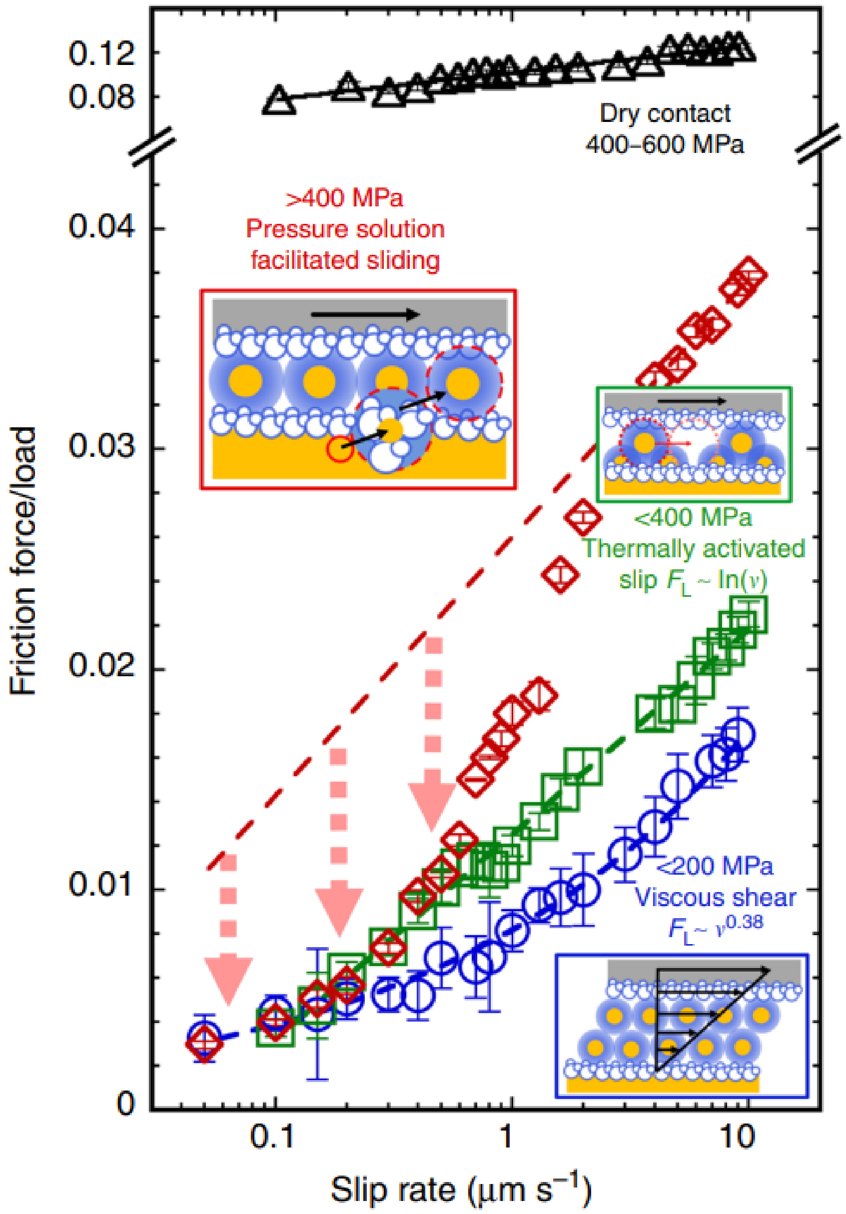

Figure 2: Rate-strengthening frictional strength of a single-asperity contact between calcite and an AFM tip in a 100 mM $CaCl_2$ solution (after Diao and Espinosa-Marzal 2018). AFM: atomic force microscopy.

Table 1: Static friction coefficient of minerals under different humidity conditions (data from Horn and Deere 1962).

Mineral	Oven dried	Saturated
Rose quartz	0.13	0.45
Microcline feldspar	0.12	0.77
Calcite	0.14	0.68
Muscovite	0.43	0.23
Chlorite	0.53	0.22

water, depending on the kind of minerals. For layer-lattice minerals, such as muscovite and chlorite, water causes a marked reduction of the friction coefficient, whereas for massive-structured minerals, such as quartz, feldspar and calcite, there is evidence of an increase in friction when water is present. This behaviour could be explained by invoking dissolution by water of impurities which were lubricating the material surface and then, after the removal of the thin film of impurities, the material shows higher friction along the flattened surface (Lambe and Whitman 1969). In this respect, based on the discussed evidence

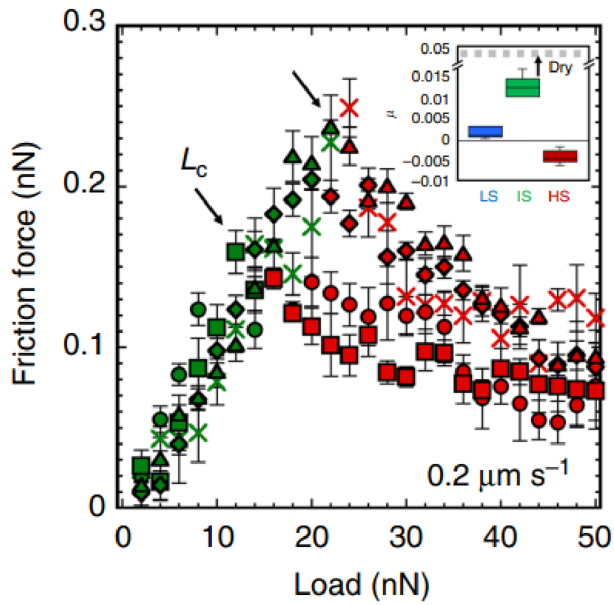

Figure 3: Friction between calcite and an AFM tip as a function of load in $CaCl_2$ solutions at sliding speed of 0.2 μm/s (after Diao and Espinosa-Marzal 2018).

from literature, one could deduce that dissolution of asperities facilitates slip and, on the contrary, dissolution of impurities may increase friction.

In Figure 4, values of the friction coefficient for quartz are reported as a function of the mineral surface roughness for different conditions in terms of cleaning of the surface. The data refer to tests on ground surfaces (Bromwell 1966; Dickey 1966; after Lambe and Whitman 1969) and, as a confirmation of the interpretation reported above, no influence of water on the friction can be detected for accurate cleaning of the surfaces, where plausibly impurities were absent. Differently, for a less- or not cleaned surface, that is, flattened surface with impurities (Fig. 4), water acts as an anti-lubricant because of its ability to dissolve impurities.

From the figure, it is also evident that the lubricant effect of the impurities decreases with increasing surface roughness: the influence of the type of cleaning vanishes on friction for very rough surfaces, with asperities of 1.5 μm (Lambe and Whitman 1969). It is expected if the impurities layer acts like epilamine lubricant (Bowden and Tabor 1964), that is, a sort of very thin layer of fluid interposed between the two solid surfaces, or like isolated nano- and micro-pillows whose slippage is stopped by asperities.

This experimental evidence concerning minerals, as well as that revealed by materials at the nanoscale, should guide the interpretation of the lubrication response of rocks and soils at a different scale, although composition and structure of these geomaterials are more complex than for a crystal or a homo-mineralic surface. In the following, the lubrication effect of water on geomaterials will be discussed first at the grain scale to connect more easily the experimental observations to the basic behaviour discussed above; thereafter, the response to lubrication of rocks and soils at the sample scale will be examined.

3 Lubrication Effect at the Grain Scale

Researchers have paid considerable attention in the last few years to theoretically and experimentally investigate the behaviour of soils at the microscale and, in general, by multi-scale approaches (Soga and O'Sullivan 2010; Yimsiri and Soga 2010; O'Sullivan 2011; Senetakis et al. 2013; Huang et al. 2014; Otsubo and O'Sullivan 2018; Li et al. 2019; Sandeep and Senetakis 2019). Many micromechanical tests have been carried out on grains and particles to deduce their frictional properties. In some cases, the tests have been performed also with reference to both dry and wet (or immersed) conditions for the granular material. Sandeep et al. (2019) and Marzulli et al. (2021) made micromechanical investigations of the normal and shear contact behaviour of two different soils: the lunar regolith simulant DNA-1A (Marzulli and Cafaro 2019; Cesaretti et al. 2014) and Ottawa sand (OS), which are a grinded volcanic soil and a quartz sand, respectively. The authors carried out the tests using an interparticle loading apparatus (Senetakis and Coop 2014; Nardelli et al. 2017), with a shearing rate of about 0.03 μm/s. The wet condition of the grains was achieved by three ways: grains immersed in water and tested, placed in water for 3 days and tested directly (not immersed during testing) and placed in water for 3 days and tested in an immersed condition.

Table 2 summarises the results obtained by the authors in terms of bulk (φ'_{bulk}) and interparticle (φ'_{μ}) friction angles, together with some indication of the grain morphology for the two soils, quite different in roughness. The values of φ'_{μ} reported in the table pertain to microtests carried out at 1 N normal contact force. It is worth noting that DNA-1A grains exhibit much higher friction resistance than OS, probably due to the difference in roughness.

Looking at the influence of water, at 1 N normal contact force, the interparticle friction angle of DNA-1A, deduced by steady-state (nominal) tangential force, is greatly affected by humidity: indeed, φ'_{μ} is 21° and 30° for the dry and wet conditions, respectively (Table 2). However, an interesting behaviour can be observed varying the normal

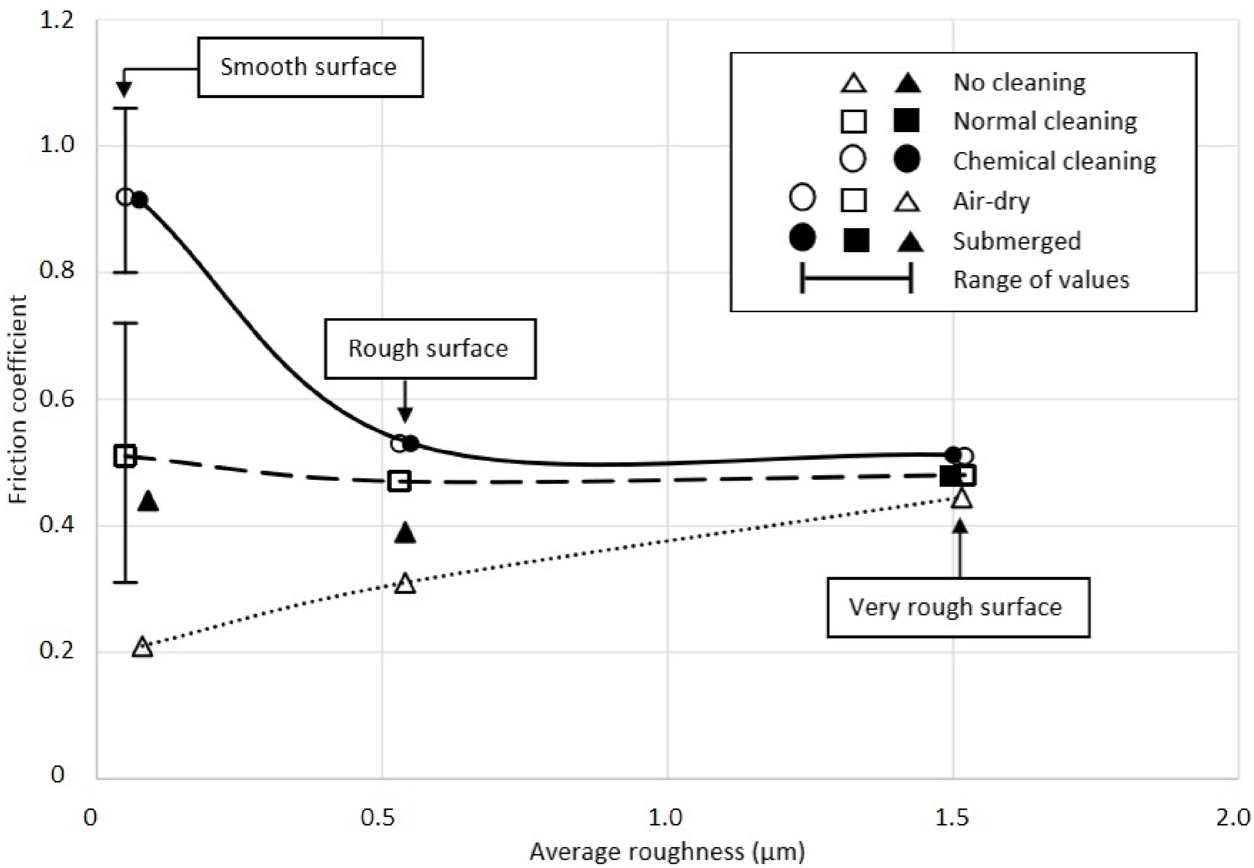

Figure 4: Friction coefficient of quartz (after Lambe and Whitman 1969, data from Bromwell 1966 and Dickey 1966; replotted).

Table 2: Morphological and friction parameters for two granular soils (DNA-1A and OS) with different roughness, under both dry and wet conditions; the interparticle friction angle is assessed based only on tests carried out at 1 N normal contact force (data from Marzulli et al. 2021).

Material	Particle size (for microtest), mm	Hardness, GPa	Roundness	Roughness, nm	φ'_{bulk} low stresses range (°)	φ'_{bulk} medium–higher stresses range (°)	φ'_{μ} (°)
DNA-1A dry	1.0–1.8	0.3	0.6	1476	47.9	40.8	21
DNA-1A wet					45.9		30
OS dry	0.5–0.8	5.8	0.8	204	45.0	36.5	7.6
OS wet					40.8		-

DNA-1A: lunar regolith simulant; OS: Ottawa sand

contact forces. In Figure 5, showing the interparticle friction coefficient versus normal force for DNA-1A at different humidity conditions, a normal force threshold can be identified (Marzulli et al. 2021) between 2 and 3 N, marking a transition from anti-lubricant to lubricant action of the water. According to Marzulli et al. (2021), this phenomenon could be related to the asperities' damage generated at the higher contact normal stresses. However, in this case, the interpretation is complex also because the particle surface is not homo-mineralic.

In the already mentioned study of Diao and Espinosa-Marzal, which was carried out at the nanoscale, there was evidence that the presence of aqueous solution leads to weakening of the frictional strength of the single-asperity contact compared to dry conditions (Fig. 2), and that the dissolution process is faster at high normal stresses. The

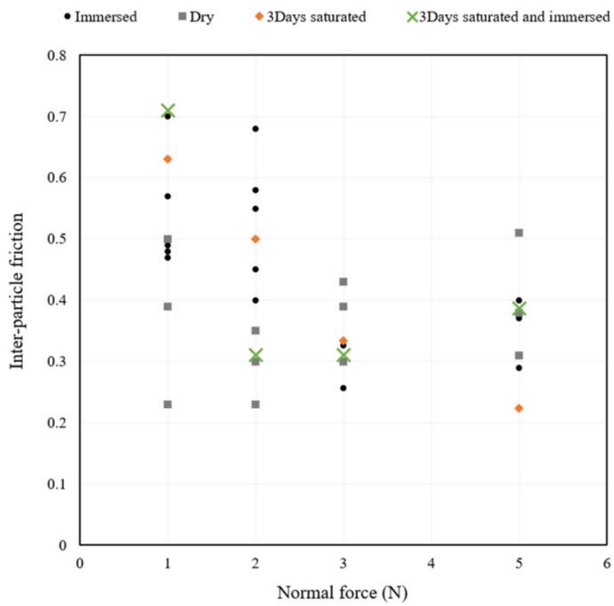

Figure 5: Interparticle friction versus normal force for DNA-1A lunar regolith simulant at different humidity conditions (after Marzulli et al. 2021).

data from Marzulli et al. seem to indicate that the incidence of water on the friction of asperity contacts may depend on the normal stresses these contacts are subjected to, although in this case, the asperity chemical dissolution is questionable and physical factors should be invoked. In both cases, the experimental evidence suggests that the efficacy of the water lubrication is related to the current level of the interparticle contact stresses.

4 Lubrication Effect on Failure Surface Friction

4.1 Experimental evidence for rocks

The number of studies on the influence of water on the rock fracture shear strength is relatively limited, compared with investigations on the water-induced degradation of intact rocks (Li et al. 2020). In general, a clear effect of water lubrication on the shear strength can be recognised. In Table 3, values of the basic friction angle, φ_b, for several rocks under both dry and wet conditions are reported (Barton 1973; Alejano et al. 2012). In all cases, the effect of water lubrication is evident, although the decrease in friction angle may vary in a wide range.

Li et al. (2020) carried out direct shear tests on granite and sandstone fracture samples under three different moisture conditions: dry, surface wet (i.e. the fracture surfaces are wet, while the matrix is dry) and saturated (i.e. the entire sample is wet). The shear test started immediately after the surfaces were wetted to avoid rock weakening due to chemical reaction and, thus, to isolate the physical lubrication effect of water on sliding. The authors tested both flat fracture and rough fracture samples. In Table 4, pertaining to the flat fracture samples, the dependency of the basic friction angle on the moisture condition is shown. For both granite and sandstone, the effect of water lubrification is evident. Moreover, the values of φ_b are almost identical for the tests under surface wet and saturated conditions. According to Li et al. (2020), this fact indicates that the basic friction angle is only controlled by the surface condition for the same material.

Table 3: Shear strength of rock fractures under dry and wet conditions (data from Barton 1973; Alejano et al. 2012).

Rock type	φ_b (°)	
	Dry	Wet
Mudstone	32	29
Siltstone	32	30
Limestone	34	31
Sandstone	31	29
Marble	49	42
Shale	29	21
Granite	33	31

Li et al. also measured, on the rough fracture samples, the reductions of asperity heights owing to shear under normal stress of 10 MPa. They found that the damage mainly happened at the top of each asperity, and that the largest loss of asperity volume occurred on the dry fracture surfaces, for both granite and sandstone, that is, the presence of water reduces the damage of asperities. In this respect, it should be investigated how during sliding, abrasion changes the asperities' morphology (Mei and Wu 2021) because at a deeper level of analysis, the friction evolution during sliding should be seen as a transient process. According to Braun et al. (2021), who investigated the frictional properties of sand-based, 3D-printed materials, progressive sliding can influence the friction due to the wear of asperities, which is accompanied by gouge creation due to granular debonding during sliding (Fig. 6), and the applied normal stress can have a non-negligible effect on the asperity wear. The interplay between this phenomenon, which could also occur in real faults (Marone and Scholz 1989; Rattez et al. 2018), and the

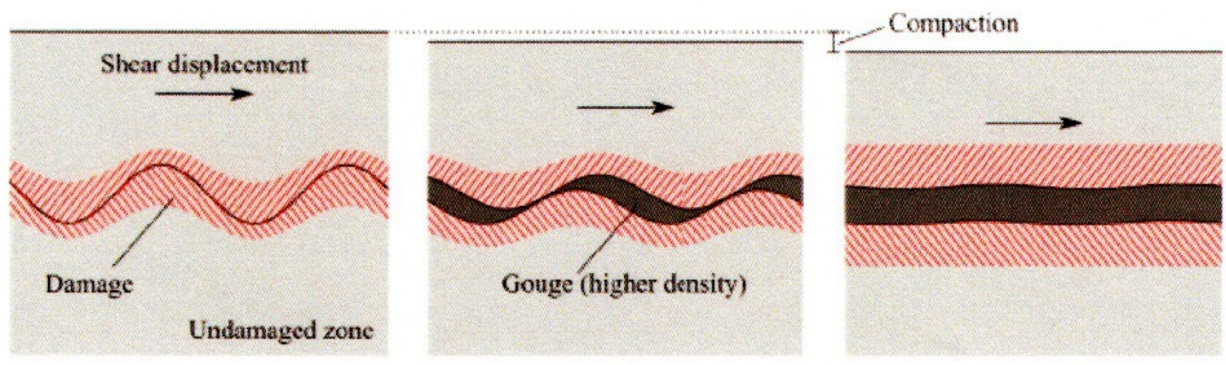

Figure 6: Schematic representation of gradual wear of asperities. Abraded grains form a gouge layer between the interfaces (after Braun et al. 2021).

Table 4: Measured values of φ_b under different moisture conditions for granite and sandstone (data from Li et al. 2020).

Rock type	Moisture condition	φ_b (°)
Granite	Dry	33.46
	Wet surface	30.59
	Saturated	30.38
Sandstone	Dry	35.30
	Wet surface	32.92
	Saturated	32.62

presence of water in determining the interface lubrication effect still requires research efforts to be fully understood.

Effect of water lubrication on peak and residual friction angles was also detected for marls. Direct shear tests were carried out by "Istituto sperimentale modelli e strutture", ISMES (1982) on big specimens of Campolattaro marls, which represent the foundation rocks of an earth dam (Jappelli 2003, 2005). The effect of water on the strength of these marls was also compared to the effect of the joint orientation with respect to the shearing plane (ISMES 1982; Table 5). Cubic specimens of 20 × 20 × 20 cm size were tested after incorporating the samples in a PAGEL mortar (E = 35,000 MPa). To saturate only the joint chosen as the sliding surface, a small hole was realised in the middle of the specimen (Fig. 7). The tests in the shear box were strain controlled at a rate of 0.06 mm/min. In that experimental campaign, both the peak and the residual strength envelop were deduced, but in Table 5, only the residual parameters are reported, since they should refer much more properly to a sliding friction resistance. In the table, two values of friction angle for each condition are reported, that is, the average value and the value coming from linear regression. The wetted samples exhibited a friction angle much lower than that pertaining to the dry samples, for equal sample orientation (i.e. parallel to the rock joint): the reduction was of about 20°.

From the data shown above, it can be also deduced that the lubrication of water affects the residual strength much more than the orientation of the rock joint: for the same dry condition, friction angles of 38° and 44° were found for parallel and orthogonal sample orientation with respect to the joint, respectively, whereas the friction angle for wet condition and parallel orientation was found to be 16°–18° (Table 5).

Strong dependency of shear strength on the water content for marl fractures was already found by Pellet et al. (2013), who observed that friction angle drops from 22° for a dry fracture to 12° for a saturated fracture and the fracture cohesion decreases from 0.41 MPa under dry conditions to 0.32 MPa under wet conditions.

To summarise, it seems that for rocks, at least under the ordinary stress levels reached during mechanical tests, water lubrication always causes a reduction of the frictional strength along fractures. The changes in the strength of asperities and the basic friction angle induced by water are considered as the two primary factors influencing the shear behaviour of wetted rock fractures (Li et al. 2020). The magnitude of this reduction, that is, the efficacy of water lubrication, depends on several factors, among which, also based on studies carried out at the nanoscale and the grain scale, the normal stresses and the sliding rate can be mentioned.

4.2 Experimental evidence for soils

Research on the effect of water on grain interaction is rather scarce (Wils et al. 2015). Experimental data by element testing for direct comparison of soil frictional response

Table 5: Values of residual friction angle of Campolattaro marls for different conditions of humidity and shearing direction (data from ISMES 1982).

Sample joint	Shearing direction	Number of data	Friction angle by linear regression (°)	Average friction angle (°)
Saturated	Parallel to joint	8	17.7	16.3
Dry	Parallel to joint	9	38.0	37.8
Dry	Perpendicular to joint	8	44.4	44.5

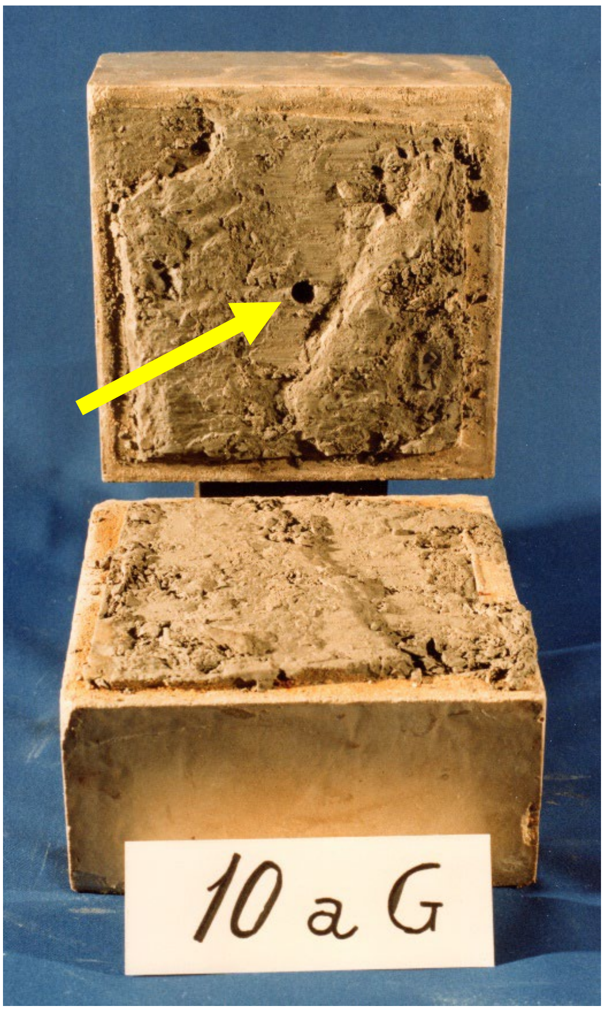

Figure 7: Campolattaro marl specimen subjected to direct shear test (the arrow indicates the hole in the middle for the rock joint saturation) (after ISMES 1982)

under dry and saturated conditions are not numerous. Although isotropic and one-dimensional compressions involve soil friction only indirectly, in terms of the intergranular friction governing the stress redistribution within the specimen, and the overall friction acting on a given surface is quite a different problem, comparison of compression tests on dry and wet sandy soils could provide some preliminary indications. In this respect, the behaviour of crushable sand was found by Wils et al. (2015) to be significantly affected by water. According to Ham et al. (2010), water causes a notable reduction of the first crushing strengths of weathered granite soils, which are associated with the breaking of corners and asperities. Miura and Yamanouchi (1975) found that saturated Toyoura sand was more compressible than dry Toyoura sand under isotropic compression at high pressures (up to 50 MPa). Uygar and Doven (2006) found, for a quite uniform sand with quartz and calcite as the main mineral constituents, a compression index under saturated condition higher than for the dry soil, irrespective of the Relative Density. Differently, Marzulli and Cafaro (2019) found practically the same compression index for dry and submerged DNA-1A lunar simulant.

Much more important for the aim of this review are results from shear tests on soil samples. Horn and Deere (1962) report that the shearing resistance of a fine Ottawa sand, as measured during direct shear tests, was unaffected by variations in surface moisture, whereas the frictional properties of highly polished quartz are greatly affected by such variations. Since the particles of Ottawa sand are almost pure quartz, they believe that this apparent paradox can be explained by invoking the roughness of the grains as a factor which makes negligible the anti-lubricating action of water on quartz.

Horn and Deere also measured, by means of direct shear tests, the drained shearing resistance of powdered muscovite, which they found to be very sensitive to moisture variations. The friction angle drops from 27°, for oven-dried condition, to about 16°, for saturated (drained) conditions. Horn and Deere, therefore, highlight different frictional responses to water lubrication for granular soils that are composed of massive-structured minerals and soils with minerals having layer-lattice structures.

As already mentioned, Marzulli et al. (2021) investigated the mechanical behaviour of Ottawa sand (OS) and a lunar regolith simulant (DNA-1A) under both dry and wet conditions by comparing the micromechanical test results to element testing behaviour. At the macroscale, the wet condition was achieved by carrying out conventional direct shear tests on submerged

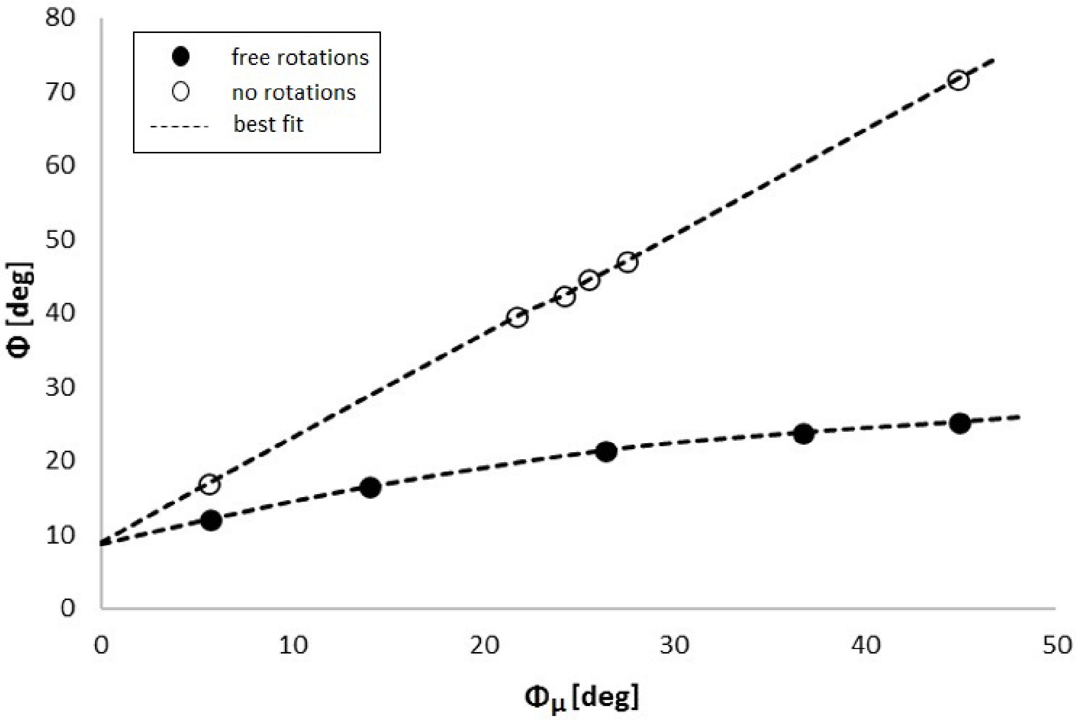

Figure 8: Bulk friction as a function of interparticle friction: 2D DEM results (after Calvetti and Nova 2004; replotted)

specimens at low vertical stresses (up to about 30 kPa). Some differences (2°–4°) in the bulk friction angles between wet and dry conditions were found for the two soils, as shown in Table 2. The table also shows the friction angles of the soils measured at higher confining stresses for dry condition only (40.8° and 36.5° for DNA-1A and OS, respectively). The influence of water on the bulk friction found at low stresses is, however, much smaller than that found at the microscale for 1 N normal contact force. This behaviour seems to confirm what Horn and Deere stated for granular soils that are composed of massive-structured minerals.

On the whole, the literature data for soils do not seem to outline a clear and unique bulk behaviour in terms of friction response to water lubrication, differently from rocks. It should be kept in mind that for granular soils, the overall shear strength of the specimen along the failure plane arises from both the sliding resistance and the rolling resistance of each particle or grain (Lambe and Whitman 1969), whereas for intact rocks undergoing fracturing, the rolling contribution should be absent and sliding is the only mechanism which takes place. This fact implies that for granular soils, the kinematic constraints of the grains will influence the relationship between interparticle (contact) friction angle and bulk friction angle, that is, the relationship between microscopic and macroscopic friction. Moreover, saturation of the contact force distribution and the mean coordination number with respect to the microscopic friction coefficient (Thornton 2000; Blair et al. 2001) can be reached. Discrete element method, DEM, models of assemblies of free round particles, that is, without rotational springs, are characterised by very low friction angles, irrespective of the interparticle friction angle (Calvetti 2008). This evidence was experimentally first observed by Skinner (1969) and was confirmed by means of DEM numerical simulations on 3D (Suiker and Fleck 2004) and 2D (Calvetti and Nova 2004; Fig. 8) assemblies of circular elements. These studies also suggest that preventing particle rotations leads to a bulk friction angle that will be a linear function of the interparticle friction angle. For soils, the assumption of no rotations should correspond to very rough grains, whose asperities create strong interlocking.

It is reasonable that the kinematic constraints, that is, the degree of interlocking, of grains of a real soil are intermediate of the two extreme conditions discussed above, that is, free rotations and no rotations. It follows that, even when at the scale of the single grain water lubricates, affecting the interparticle friction angle, not necessarily the overall lubrication effect on the friction of the granular assembly will be evident.

Crushing of sands may change particle shape and particle surface roughness, also depending on the initial soil grading (Altuhafi and Coop 2011). It is thus expected that during shearing, the crushing may change dramatically the interlocking and kinematic constraints of grains and particles, which in turn should change the water lubrication effect at the macroscale; however, focusing on this behaviour is out of the scope of the present paper. Further research on the interplay between crushing and evolution of the water lubrication effect at the macroscale would provide promising results.

5 Conclusions

Approaching the frictional response of rocks and soils to water lubrication requires multiscale studies; some of them have been discussed in this paper. Friction characteristics of homo-mineralic surfaces, both dry and wet, as well as the interparticle shearing behaviour, can represent the benchmark response for geomaterials. However, inferring the bulk lubrication effect on grain assemblies from the water effect detected at the microscale is still an open problem. Several factors must be considered at the same time, like the presence of asperities and impurities on the grain surface, the sliding rate, the fluid composition and the grains' interlocking.

At the grain scale, it seems that a threshold of normal contact stresses exists, which marks the transition from anti-lubricating to lubricating effect of water during sliding of two in-contact grains. At a low sliding rate, dissolution and abrasion of the asperities could occur at the same time, although it is difficult to isolate the chemical and physical processes contributing to the efficacy of water lubrication.

Overall, the lubrication effect on rocks seems to be more easily interpretable. Differently, it has been shown that for soils undergoing shearing, even when at the grain scale water affects friction, the overall effect on the friction of the granular assembly may not be evident, probably depending on the kinematic constraints characterising the soil particles and on saturation of the contact force distribution. Further theoretical and experimental research should address comprehension of the mechanical factors controlling this behaviour.

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