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Influence of engineered roughness microstructures on adhesion and turbulent resuspension of microparticles

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► To cite this version:

Amir Banari, Klaus Graebe, Martin Rudolph, Ehsan Mohseni, Pierre Lorenz, et al.. Influence of engineered roughness microstructures on adhesion and turbulent resuspension of microparticles. *Journal of Aerosol Science*, 2023, 174, pp.106258. 10.1016/j.jaerosci.2023.106258 . hal-04232948

HAL Id: hal-04232948

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Submitted on 11 Oct 2023

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1 **1. Introduction**

2 **1.1. General context**

3 The detachment of micron particles from a wall surface by a turbulent gas flow, hereafter
4 referred to as resuspension, is present in many natural and industrial environments. Examples
5 are diverse and range from pathogens detaching from indoor and outdoor surfaces (Bourouiba,
6 2021; Hospodsky et al., 2012) to pollen (Banari, Hertel, Schlink, Hampel, & Lecrivain, 2023;
7 Visez et al., 2019), microplastics (Amato-Lourenco et al., 2020), volcanic ash (Del Bello et al.,
8 2018), soot (Cho et al., 2021), minerals in arid environments (Klose & Shao, 2013), radioactive
9 dust (Gregory Lecrivain, Vitsas, Boudouvis, & Hampel, 2014; Shinohara & Yoshida-Ohuchi,
10 2021) and earth particles adversely transported during extraterrestrial explorations (Mikellides
11 et al., 2020).

12 **1.2. State-of-the-art and current limitations**

13 In the simplest scenario, where an individual particle initially sits at rest on a wall surface,
14 resuspension occurs when either the aerodynamic drag force or torque overcomes its adhesive
15 counterpart (Henry & Minier, 2014a; Henry, Minier, & Brambilla, 2023). Wall surfaces are
16 however rarely smooth and wall roughness significantly affects the adhesion force pinning the
17 particle to the substrate (Brambilla & Brown, 2020). Many experiments performed with the
18 ambient fluid at rest support the idea that an increased wall roughness results in a lower
19 adhesion force. Early experiments were performed by vertically pulling rubber particles from a
20 polymer PMMA wall surface (Fuller & Tabor, 1997). By increasing the wall roughness from
21 about 0.1 to 1 μm , the authors reported a ten-fold reduction in the adhesion force. In their work,
22 the wall roughness was achieved by bead-blasting the samples. Later, Atomic Force
23 Microscopy (AFM) was used to precisely determine the pull-off force needed to detach glass
24 spheres with a 20- μm diameter from a titanium wall surface (Rabinovich, Adler, Ata, Singh, &
25 Moudgil, 2000). By increasing the surface wall roughness from 0.17 to 1.60 nm, the authors
26 reported an almost four-fold reduction in the adhesion force. Similar conclusions were recently
27 drawn for spherical tungsten particles with a 20- μm diameter pulled off a tungsten surface
28 (Peillon et al., 2019). Compared to the nanometer range, it was found that a wall roughness in
29 the micrometer range results in a decrease in the adhesion force by up to two orders of
30 magnitude.

31 In addition to AFM measurements, a few experimental studies have investigated the role played
32 by the substrate roughness on particle resuspension in a turbulent gas flow (Barth, Preuß,
33 Müller, & Hampel, 2014; Brambilla, Speckart, & Brown, 2017; Brambilla, Speckart, Rush,
34 Montano, & Brown, 2018; Goldasteh, Ahmadi, & Ferro, 2013; Jiang, Matsusaka, Masuda, &
35 Qian, 2008; Mukai, Siegel, & Novoselac, 2009; Peillon et al., 2022). In the work by Jiang et al.
36 (2008), spherical glass and PMMA particles with diameters ranging from about 10 to 40 μm
37 were resuspended from stainless steel substrates. The wall roughness of the substrates ranged
38 from 10 nm to 1.64 μm and was obtained by manual abrasion with sandpaper. It was showed
39 that the greater the wall roughness, the smaller the threshold velocity ($u_{0.5}^*$), here defined as the
40 friction velocity, at which 50 % of the particles resuspend. Conversely, this trend was not
41 observed for the lighter PMMA particles when the wall roughness exceeded 0.3 μm , thereby
42 not corroborating the fact that increased wall roughness triggers increased material detachment.
43 One possible reason for this unexpected behavior is the increased near-wall turbulence
44 generated by the larger wall roughness and the lower inertia of the PMMA particles. Further
45 experimental studies on the determination of the threshold velocity with increasing wall

1 roughness have been done by Mukai et al. (2009). In their work, salt particles with sizes ranging
2 from 1 to 20 μm were resuspended from linoleum and galvanized metal plates, whose surface
3 roughness was estimated from literature data at 0.08 and 0.15 mm, respectively. With relatively
4 high turbulence intensity, no significant difference in the threshold velocity was observed. In a
5 later experiment (Barth et al., 2014), smooth glass plates with a wall roughness of 25 nm and
6 abraded steel plates with a wall roughness set to 0.08, 0.92 and 1.54 μm were used. The diameter
7 of the glass beads ranged from 25 to 45 μm . The authors could not report any correlation
8 between wall roughness and threshold velocity.

9 To simulate particle resuspension, computationally tractable models have been suggested. In
10 this context, many authors have described the wall roughness with simplified descriptions at
11 the level of the particle size. One approach is to describe the rough surface of the substrate as a
12 smooth plate covered with randomly placed hemispherical asperities (Cui & Sommerfeld, 2022;
13 Guingo & Minier, 2008; Henry & Minier, 2014b; Rabinovich et al., 2000; Ziskind, Fichman,
14 & Gutfinger, 1997). Such geometrical representations make it possible to conveniently estimate
15 an adhesion force with a van der Waals formulation based on asperity and particle radii.
16 Alternative representations of the roughness elements exist. Nasr, Ahmadi, Ferro, and
17 Dhaniyala (2019), for instance, described the wall roughness with a two dimensional sinusoidal
18 function and Hu, Johnson, and Meneveau (2023) with multi-fractal roughness elements.
19 Simulations with the above adhesion models, which are often coupled to a force-balance model
20 to simulate the rupture of the adhesive bond by aerodynamic forces, generally deliver matching
21 threshold velocities for various roughness lengths. In addition, such simulations allow a detailed
22 investigation of the triggering resuspension mechanisms, such as the particle rocking with an
23 asperity (Brambilla et al., 2018; Guingo & Minier, 2008), that is otherwise difficult to observe
24 experimentally. In some other studies (Soltani & Ahmadi, 1999), the roughness of the particle
25 surface is also taken into account. While numerical simulations are out of the scope in this
26 study, it is important to note that the validation of the existing models is often hampered by the
27 lack of precise information on roughness characteristics, especially with respect to shape and
28 curvature of the roughness elements as well as their exact spatial repartition on the substrate
29 (Henry & Minier, 2018).

30 **1.3. Objectives of this work**

31 Following the brief overview of the above state-of-the-art, wall roughness appears to play a role
32 in particle resuspension. Experiments on particle resuspension by turbulent gas flows have been
33 carried out, in which the wall roughness of the substrates has been changed by mechanical
34 abrasion, for instance with sandblasting or sandpaper. The reported results are somewhat
35 controversial and do not always support the assumption, that an increased wall roughness causes
36 particle resuspension to occur at a lower friction velocity. The wall roughness of real-life
37 substrates is random in nature, with wall asperities highly inhomogeneous in space and size.
38 This in-turn leads to an intricate interaction between wall and particle surfaces that continues
39 to challenge the modeling, especially in terms of adhesion force formulations (Henry & Minier,
40 2018). Available resuspension models rely on an ideal description of the wall surface, which
41 aims at being statistically representative of those used in experiments. Despite continuous
42 efforts in terms of modeling, this ideal surface representation still fails to fully capture the
43 chaotic and nonlinear nature of experimentally used rough surfaces. The objectives of this work
44 are twofold:

- first, to determine experimentally the adhesion force between an individual spherical microparticle and a wall surface artificially roughened with a structured arrangement of identical and geometrically simple roughness elements,
- second, to link it with the resuspension of a particle cloud initially at rest on the same wall surface and exposed to a turbulent gas flow.

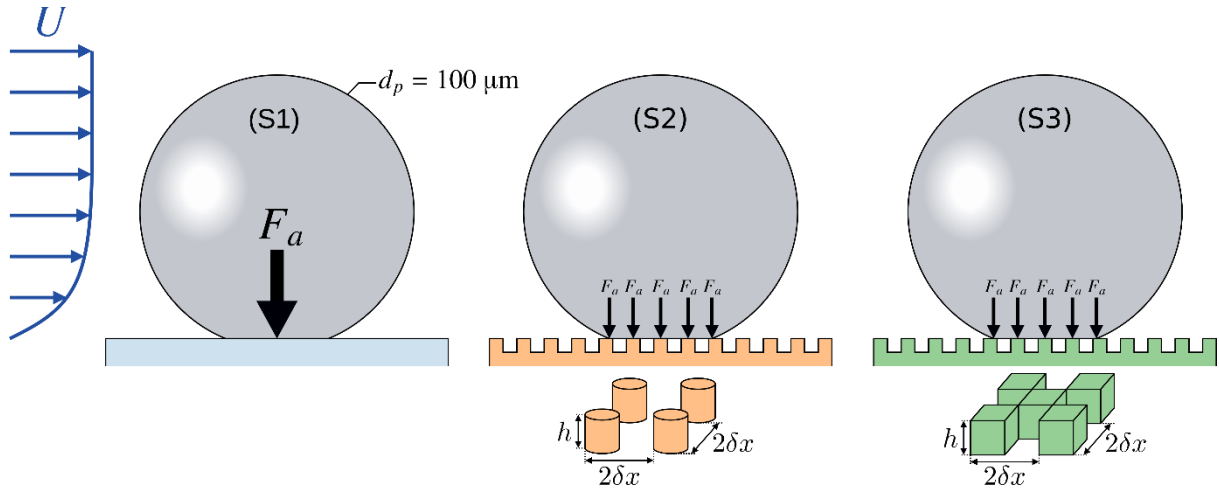
To the authors' knowledge, we provide here first experimental data obtained by using a structured arrangement of well-defined asperities as replacement to naturally arising asperities with uneven size distribution and random placement. Adhesion force measurements with an AFM and particle remaining fraction against gas velocity in a wind channel are here reported for a reference smooth surface (S1) and two artificially roughened surfaces (S2 and S3). The well-defined asperities in S2 and S3 are represented by cylindrical micropillars and microcubes.

The paper is organized as follows: the methods and experimental procedure are described in Section 2, while the results obtained are reported and analyzed in Section 3.

2. Methods

2.1. Scenarios

Three experimental scenarios are presently investigated. In the first reference scenario (S1) illustrated in Figure 1a, an individual spherical particle is initially at rest on an unaltered and aerodynamically smooth horizontal wall surface and is exposed to a turbulent gas flow. The arrow F_a pointing downwards represents the adhesion force. We hereafter define a "smooth" wall surface, as a surface with roughness features in the nanometer range. The first-order roughness is typically below 5 nm, that is a size by several orders of magnitude lower than the asperity height (h) set in the scenarios S2 and S3. In the second scenario (S2) illustrated in Figure 1b, the wall surface of the substrate is artificially roughened by well-defined microasperities arranged in a square lattice. Each asperity is a cylindrical micropillar with a diameter set to $\delta x = 5 \mu\text{m}$ and a height $h = 5 \mu\text{m}$. The separation distance between two asperities is also δx . As shown later, the cross-sectional contour of a micropillar is not truly a circle but rather a square with rounded corners. In the third scenario (S3) illustrated in Figure 1c, the asperities are microcubes arranged in a two-dimensional face-centered layout reminiscent of a chessboard. The side length of each microcube is set to $\delta x = 7.5 \mu\text{m}$ and the height to $h = 5 \mu\text{m}$. It is here postulated that the total adhesion force $\sum(F_a)_i$ originating from the rough surfaces S2 and S3 is lower than that from the reference substrate S1. Because the contact area between a single particle and the rough substrate is smaller, we anticipate that resuspension occurs at a lower gas velocity (U). Note that Figure 1 is purely illustrative and aims at describing our postulate. The softness of the glass particles, from which the adhesion forces can be established from theories of contact mechanics, for instance with the JKR or the DMT model (Ciavarella, Joe, Papangelo, & Barber, 2019), is deliberately exaggerated.



1 **Fig. 1:** Schematics of the presented experimental tests. In the reference scenario (S1), a
 2 spherical particle sits on a smooth surface. The adhesion force is F_a . In scenarios (S2) and (S3),
 3 the particle sits on a structured arrangement of microcubes and cylindrical micropillars. It is
 4 postulated, that in S2 and S3, the resulting adhesion force $\sum F_a$ is lower than the reference value
 5 in S1. For illustration purposes, the deformation of the particles, from which the adhesion
 6 forces can be established with theories of contact mechanics, has been exaggerated.

7 2.2. Particles

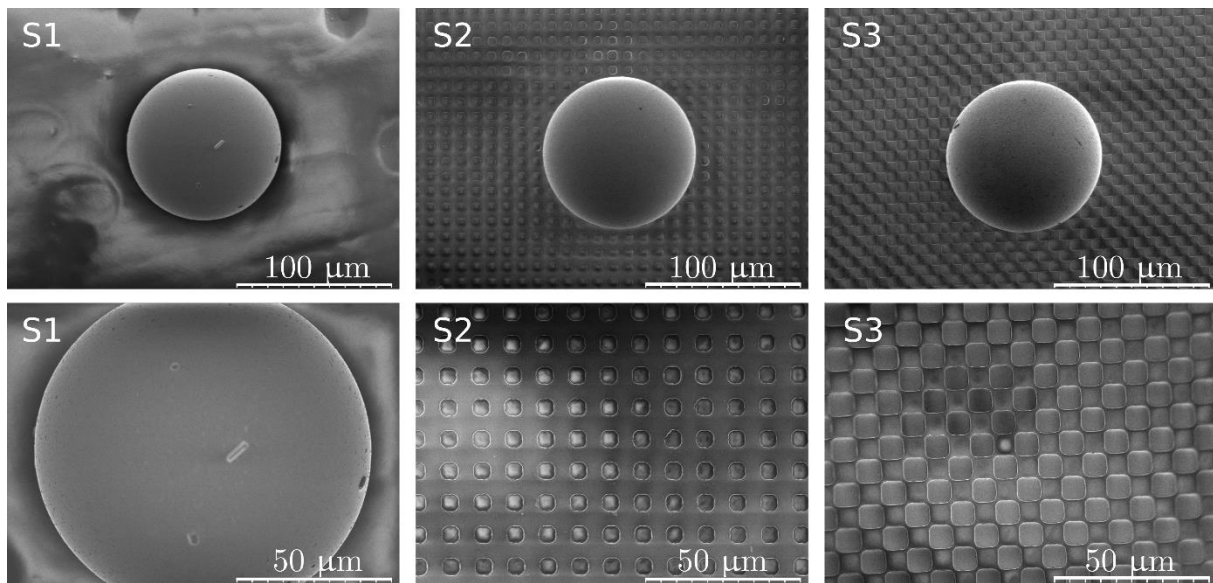
8 The particle beads are here spherical and made of soda lime-silicate particles (GBL100,
 9 Association of Powder Process Industry and Engineering). They are highly monodispersed in
 10 size and have a density of $\rho_p = 2,500 \text{ kg}\cdot\text{m}^{-3}$. With a particle-to-air density ratio $\rho_p/\rho \approx 2000$,
 11 the particles are much heavier than the ambient gas. With a particle diameter set to $d_p = 100$
 12 μm , the particles are classified as coarse to super coarse (Adebiyi et al., 2023). The particle size
 13 is, among others, representative of settling dust, pollen and ash particles (Del Bello et al., 2018;
 14 Klose & Shao, 2013; Visez et al., 2019). A further motivation behind this relatively large
 15 particle size was to have a ratio of the particle diameter to asperity height matching that reported
 16 in other experimental studies. It turned out a lot more practical to change the particle size rather
 17 than the asperity height. Here, the ratio equals $d_p/h = 20$. In the experiments performed by
 18 Barth et al. (2014) and Jiang et al. (2008), threshold velocities were obtained with a ratio of
 19 particle diameter to mean wall roughness equal to about 30.

20 2.3. Surface functionalization of the substrates

21 The three substrates presently used are wafers that are precision thin round windows (Product
 22 226-1226E, EKSMA Optics, Lithuania). These have been functionalized with one smooth and
 23 two rough coatings. The coating procedure for the rough substrates is as follows. The substrate
 24 surface is first prepared with a standard two-step wafer cleaning process, known as RCA clean.
 25 The first cleaning step is performed with a $\text{NH}_3/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ solution at $50 - 60 \text{ }^\circ\text{C}$ in an
 26 ultrasonic bath for 20 min and the second with a $\text{HCl}/\text{H}_2\text{O}_2/\text{H}_2\text{O}$ solution at $50 - 60 \text{ }^\circ\text{C}$, also
 27 in an ultrasonic bath for 20 min. The substrate is then covered with an adhesion promoter (TI
 28 Prime, Microchemicals) by spin-coating with a rotation speed of 4000 rpm and a subsequent
 29 drying at $115 \text{ }^\circ\text{C}$ for 2 min. The substrate surface is then covered with a negative photoresist
 30 (AR-N4400-10, Allresist) by spin-coating with 4000 rpm and a subsequent drying at 90°C for
 31 4 min. The resulting photoresist layer exhibits a thickness of about $5 \mu\text{m}$. Photolithographic
 32 exposure of the resist is performed with a mercury vapor lamp ($3 \times 5 \text{ s}$) using a chrome

1 lithography mask with a periodic grating. For the lithography mask in S2, squares with a 5 μm
2 side length and a 10 μm periodicity in the two lattice directions are used. Owing to the
3 lithography fabrication process, the asperities appear from the top view as squares with rounded
4 corners. For the mask in S3, squares with both edge length and period set to 7,5 μm are used.
5 The irradiated sample is tempered at 100 $^{\circ}\text{C}$ for 5 min and then developed by a developer (AR-
6 300-47) for 75 s. Following the developing process, the sample is dried at 95 $^{\circ}\text{C}$ for 2 min and
7 additionally flood-exposed with a mercury vapor lamp for 15 s. A final tempering process
8 carried out at 120 $^{\circ}\text{C}$ for 5 min is applied to improve the mechanical stability. With exception
9 of the last steps, the procedure used to fabricate the smooth reference coating S1 is the same as
10 described above, meaning that a 5- μm thin photoresist layer is present on the clean wafer
11 surface. Based on previous works (Maji, Urakawa, & Inoue, 2014; Monk, Haskins,
12 Bauschlicher, & Lawson, 2015), the Young's modulus of a typical Novolak resin (AR-N4400-
13 10) normally ranges from 3 to 6 GPa and the Poisson's ratio from 0.3 to 0.36.

14 Top-down images of a glass particle at rest on the three substrates are shown in Figure 2. The
15 micrographs were taken at different magnifications with a scanning electron microscope
16 (SEM). The smoothness of the reference substrate surface and the asperities in S2 and S3 are
17 well distinguishable. With respect to S1, the measured first-order roughness of the surface is
18 within 5 nm, that is a size by several orders of magnitude lower than the asperity height (h) set
19 in S2 and S3. Despite very few spots with damaged asperities that may have adversely occurred
20 during fabrication and/or manipulation of the substrates during the measurement campaign, the
21 quality of the coating is generally good. Further SEM images with a larger field of view can be
22 seen in the raw data material (Gregory. Lecrivain, 2023).

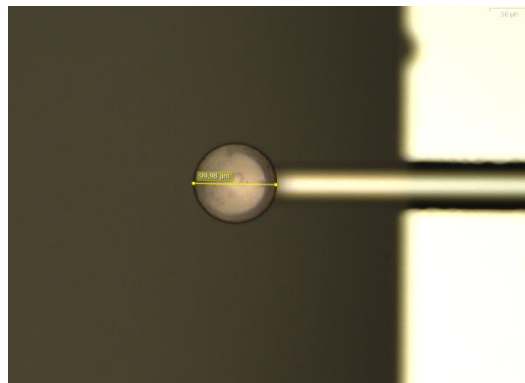


23 **Fig. 2:** Sample images of particles and three substrates (S1, S2 and S3) taken with a scanning
24 electron microscope (SEM) at two different magnifications. Color gradients in the micrographs
25 are caused by charging effects of the insulating samples during SEM image acquisition.

26 **2.4. Force measurement with Atomic Force Microscopy**

27 To measure the adhesion force distribution between a single particle and the substrates, the
28 following colloidal probe AFM-based procedure is used. A Park Systems NX12 atomic force

1 microscope is utilized for colloidal probe preparation, cantilever characterization, which
 2 includes calibration, and force-distance measurements. As illustrated in Figure 3, the colloidal
 3 probe cantilevers are prepared by gluing a representative 100 μm spherical particle, which
 4 involve Ber-Fix UV-Kleber with an All-In-One Aluminum-coated B type cantilever from
 5 Budget Sensors (Babel & Rudolph, 2019). Prior to attaching the particle, the force constant of
 6 the cantilever is determined using the procedure described in the authors' previous work
 7 (Rudolph & Peuker, 2014), which contains all the relevant details about the force constant
 8 calibration. Here, along with any other static mode colloidal probe AFM, the force constant is
 9 calibrated based on the resonance frequency of the cantilever prior to attaching the particle,
 10 which alters the resonance frequency but not the force constant. After hardening of the glue,
 11 the colloidal probe cantilever is inspected under the microscope for proper positioning of the
 12 particle. Before the first measurement, the AB-sensitivity, that is the relation between signal
 13 intensity and bending, is determined with a force-distance contact scan on a Si-wafer substrate.
 14 For the adhesion measurements, the substrates are placed under the AFM. A 30 min waiting
 15 time allows for equilibration with respect to temperature and adsorption/desorption of gas
 16 molecules under the ambient conditions. For each substrate, the force-distance measurements
 17 are performed on a square area of $100 \times 100 \mu\text{m}^2$ with a total of 256 single force-distance
 18 measurements measured in triplicates. The adhesion forces are determined from the retrace
 19 curves as the absolute maxima. The force limit is kept constant at 220 nN and the z-scanner
 20 speed is set to $0.3 \mu\text{m/s}$.



21
 22 *Fig. 3: Glass particle attached to cantilever and used for the pull-off force measurements.*

23 **2.5. Particle resuspension in the wind channel**

24 The wind channel is the same as that presented in the authors' previous work (Banari et al.,
 25 2021). We hence only recall the most salient features of this experimental set-up. The channel
 26 has a length, $L = 2 \text{ m}$, and a square cross-section $H^2 = 1 \times 1 \text{ cm}^2$, where H is the channel height.
 27 A gas flow free of any impurities is created using pressurized clean air. Each substrate is placed
 28 1.5 m downstream of the channel inlet, that is a distance large enough to achieve a fully
 29 developed turbulent flow in the measurement section. The presented experiments are performed
 30 at room temperature, that is at about $T = 15 \text{ }^\circ\text{C}$, such that the dynamic viscosity and density of
 31 the air are equal to $\mu = 17.89 \times 10^{-6} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ and $\rho = 1.225 \text{ kg}\cdot\text{m}^{-3}$, respectively. Prior to
 32 experimenting, the inner channel walls are cleaned and dried to ensure an oil- and humidity-
 33 free environment that would otherwise adversely affect the resuspension. The flow rate (Q) is
 34 varied from zero to $Q_{max} = 65 \text{ l}\cdot\text{min}^{-1}$ with an increment down to $2 \text{ l}\cdot\text{min}^{-1}$ in areas of high

1 particle detachment. This corresponds to a maximum air bulk velocity $U_{max} = 10.83 \text{ m.s}^{-1}$ and
2 a maximum bulk Reynolds number $Re_{max} = 7420$. The latter is here given by

$$Re = \rho UH / \mu, \quad (1)$$

3 where $U = Q/H^2$ is the air bulk velocity. Surface functionalization, by allowing a precise
4 control of the wall surface properties, gives rise to exciting opportunities for the fundamental
5 investigation of particle resuspension. With the help of surface functionalization, many
6 limitations associated with the chaotic nature of manually abraded surfaces can be overcome.
7 This work is however a first study and hence we limit ourselves to two roughness types and one
8 particle size. The authors are well aware that a more in-depth parameter study could be
9 performed, for example by further changing the shape of the asperities, their arrangement and
10 the particles. The data presented in this work involve a close collaboration between many
11 laboratories. Coating the wafers, taking the SEM images, measuring the adhesion force
12 distributions and performing the wind channel experiments were done at various places and
13 were quite resource intensive. Manufacturing many coatings is also expensive and will be part
14 of future studies aiming at systematically characterizing the role of wall roughness on
15 resuspension. We hence choose to keep the particle size fixed and, consequently, to focus on
16 the 100- μm glass beads since they are much larger than the typical surface roughness size. In
17 addition, resuspension is here mostly triggered when the equilibrium between aerodynamic and
18 adhesive forces is ruptured because of to the glass beads' size. Resuspension is employed as a
19 rather generic term to describe the particle detachment from a wall surface. The underlying
20 transport mechanisms, that are saltation, rolling, sliding and energy-transfer through particle
21 collisions are not addressed in this study.

22 To quantify particle resuspension from the three substrates in the wind channel, we employ a
23 conventional procedure widely used in many experimental and numerical studies. First, the
24 particles are manually and sparsely sprinkled over the substrate. The substrate, on which a
25 monolayer bed of particles now lies, is then carefully inserted into the channel test section. A
26 high-resolution camera (MotionPro Y3 HDiablo, Imaging Solutions) equipped with a
27 microscope lens (K2 DistaMax, Infinity Photo-Optical, MX-6 magnification) images a portion
28 of the substrate from the top that is a rectangular field of view with an area set to approximately
29 $2.32 \times 1.45 \text{ mm}^2$. A light source (Constellation 120E, Imaging Solutions) illuminates the
30 substrate and the particles from above. Each particle in the image is discretized into about 55
31 pixels along the diameter. The initial number of particles N_0 in the field of view is determined
32 using semi-automatic procedure. At this stage, the gas in the test section is at rest, that means
33 $Re = 0$. With ImageJ as image processing software (Schneider, Rasband, & Eliceiri, 2012), a
34 Gaussian blur is first employed. An attempt at tagging each individual particle is done by
35 finding the image maxima. The particle tags are then corrected manually. In the presented
36 experiments, the initial particle number N_0 typically varies between about 40 and 200, which
37 corresponds to an initial coverage of the field of view ranging from 9 to 47 % and to surface
38 number concentration ranging from 11 to 60 mm^{-2} , that is the particle number per square
39 millimeters. We note, that the upper bound of the interval, which is only one data set out of
40 thirty, is a bit large in terms of collision frequency compared to the average coverage. Second,
41 the air flow is increased in a stepwise manner. For each value of the flow rate, that is under a
42 constant Reynolds number, the instantaneous particle number $N(Re, t)$ in the field of view
43 rapidly diminishes until it reaches an equilibrium $N(Re, t \rightarrow \infty) = N_\infty(Re)$. Our experimental
44 observations show that equilibrium is reached well within seconds. To ensure that equilibrium

1 is reached under constant Reynolds number, several pictures of the particle bed are taken at
 2 regular time intervals. The remaining particle fraction, defined in the field of view as the
 3 number of remaining particles at equilibrium divided by that initially obtained at $Re = 0$, is
 4 given by

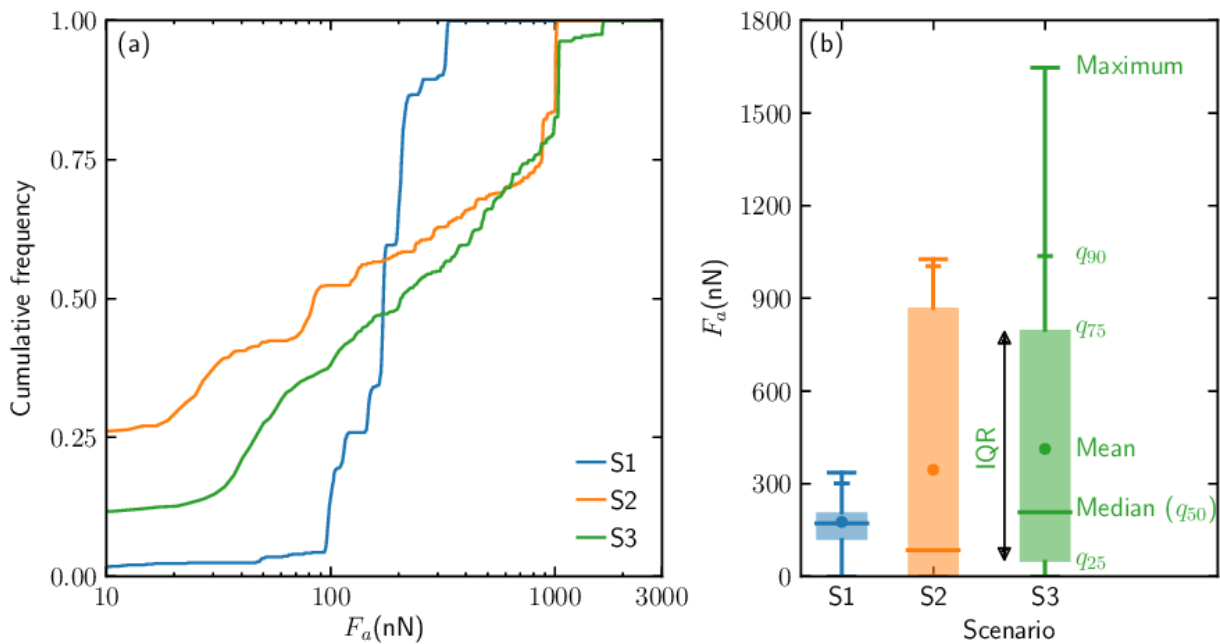
$$f_r = N_\infty(Re) / N_0. \quad (2)$$

5 The specific Reynolds number ($Re_{0.5}$) for which, $f_r = 0.5$, is defined as the threshold and
 6 indicates the critical value at which half of the particles resuspend. The thresholds associated
 7 with the bulk velocity ($U_{0.5}$) and the friction velocity ($u_{0.5}^*$) are defined in a similar way. The
 8 link between U and u^* is later explained.

9 3. Results and discussions

10 3.1. Adhesion force distributions

11 The measured adhesion forces obtained for the three substrates are shown in Figure 4a in the
 12 form of cumulative frequencies. The median adhesion forces between a single particle and the
 13 substrates S1, S2 and S3 equate $F_a = 168$ nN, 82 nN and 197 nN respectively. The median value
 14 corresponds here to the 50th percentile (q_{50}) in Figure 4, that is the force abscissa at which each
 15 curve crosses the 50% cumulative frequency. These measured adhesion forces agree
 16 quantitatively well with previous experimental data found in the literature. Using the centrifugal
 17 technique, Salazar-Banda, Felicetti, Goncalves, Coury, and Aguiar (2007) measured the mean
 18 adhesion force between a steel surface and phosphatic rock particles with diameters ranging
 19 from 20 to 50 μm . Their particles were not spherical and the root-mean-square (rms) roughness
 20 of the substrate ranged from 20 to 50 nm. In the present context, the surface of their substrate
 21 can be considered smooth. They reported mean adhesion forces between 110 to 330 nN.



22 **Fig. 4:** Cumulative frequencies (a) and box plot representations (b) of the adhesion forces F_a
 23 measured between a single glass particle and the substrates S1, S2 and S3. q_{25} , q_{75} and q_{90}
 24 are the 25th, 75th and 90th percentiles, respectively, $IQR = q_{75} - q_{25}$ the interquartile range.

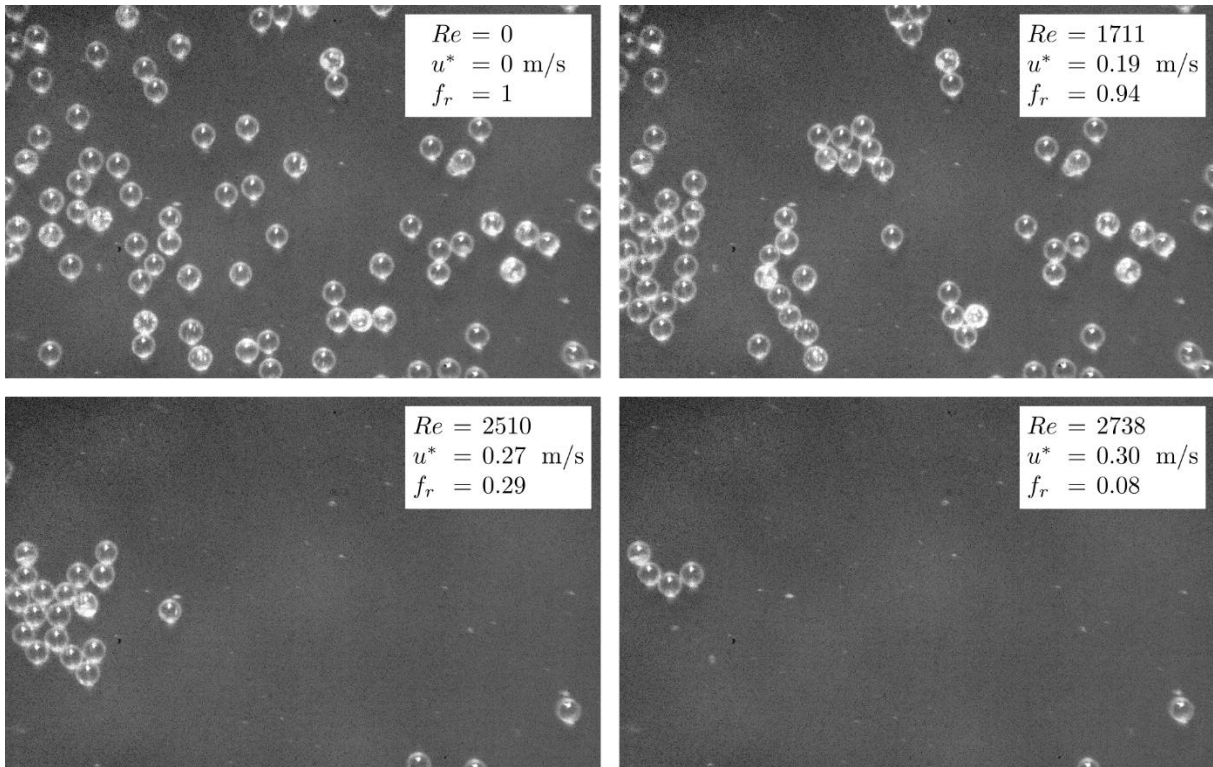
1 *The order of magnitude of the median adhesion force is the same for all substrates.*
2 *Functionalization of the substrates S2 and S3 with microasperities mostly results in a wider*
3 *and more multimodal distribution. The AFM measurements are performed with no gas flow.*

4 Using AFM, Yang, Zhang, and Hsu (2007) measured the adhesion force between a silicon wafer
5 and spherical glass beads with diameters ranging from 6 to 35 μm . In their work, the substrate
6 roughness was similar to that of our ‘smooth’ reference substrate S1, that is a few nanometers
7 in amplitude. In all scenarios, they determined mean adhesion forces ranging from 30 to 110
8 nN. They also reported, that the adhesion forces did not correlate with the bead diameter.
9 Tormoen, Drelich, and Nalaskowski (2005) also performed adhesion force measurements with
10 AFM. The substrate was a silicon wafer and the particles were glass beads with diameters
11 ranging from 10 to 40 μm . They used a first smooth silicon wafer with first-order roughness
12 below 1 nm and a second one, that was artificially roughened with a regular array of triangular
13 microridges with a periodic spacing set to 3 μm and a height to 2 μm . Their measured mean
14 adhesion forces varied between 10 and 110 nN. Interestingly, they also reported that the
15 triangular microridges gave rise to a larger force scattering often exhibiting a multimodal
16 distribution, as opposed to the unimodal distribution associated with their smooth substrate. In
17 their work, the presence of microasperities did not necessarily mean a lower mean adhesion
18 force. We draw here similar conclusions in terms of median value and scattering. The median
19 adhesion forces determined for our three substrates are relatively close to one another. The
20 cumulative frequency associated with the smooth substrate S1 (black curve) exhibits a
21 relatively sharp gradient, indicating a narrower force distribution as opposed to S2 and S3. A
22 common parameter providing information about the scattering is the interquartile range (IQR)
23 illustrated in Figure 4b, which corresponds to the difference between the 75th (q_{75}) and the 25th
24 percentile (q_{25}). The IQR for S2, respectively S3, equals 844 nN, respectively 743 nN. These
25 representative scattering values are much larger than the one associated with S1, which has an
26 IQR equal to 87 nN. The box plot in Figure 4b further illustrates the larger adhesion force
27 scattering in S2 and S3. The 90th percentile (q_{90}) associated with S2 and S3 is about three times
28 as high as that associated with reference S1. The percentile q_{90} equals 301, 1004 and 1037 nN
29 for S1, S2 and S3. The tick position of the 90th percentile relative to the maximum in Figure 4b
30 also gives indication about the likelihood of finding particle strongly adhering particles, which
31 may act as clustering seeds (see section 3.2). Further statistical values, such as the mean and
32 maximum values, are shown in Figure 4b.

33 **3.2. Particle remaining fractions**

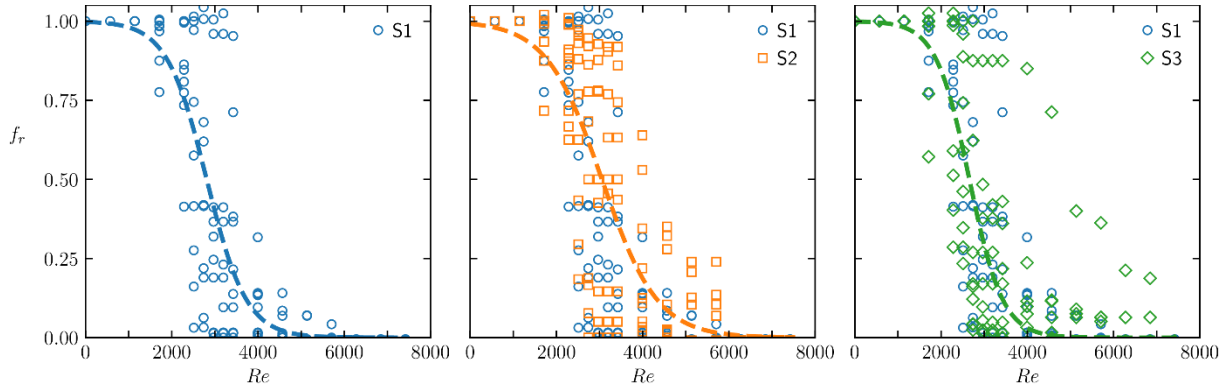
34 The results from thirty experiments performed in the wind channel are now presented. For each
35 substrate, ten experiments are carried out. All raw data are available (Gregory. Lecrivain, 2023).
36 First, a selected image sample (see Figure 5) showing an initial particle bed and its subsequent
37 equilibrium states obtained under constant Reynolds numbers is discussed. The sample is
38 shown for increasing Reynolds numbers set to $Re = 0, 1711, 2510$ and 2738 . The remaining
39 fraction associated with each image is also given. The top left panel in Figure 5 further confirms
40 that the initial particle deposit is a monolayer bed. We also note that the particles forming the
41 initial bed are never evenly spread on the surface. As expected, the remaining fraction, which
42 equates unity at $Re = 0$, decreases with increasing Reynolds number. When resuspension
43 starts, striking particle re-arrangement within the bed occurs. We observe the formation of
44 particle islands, hereafter referred to as clusters, on the surface of all three substrates. Cluster
45 formation is well distinguishable in Figure 5, top right. The measured scattering in the adhesion

1 force helps us explain cluster formation. Some particles adhere more strongly than others to the
 2 substrate and only detach at higher wind speed. Such strongly adhering particles hence act as
 3 clustering seeds. Other downstream particles, which are loosely attached, roll and eventually
 4 come to a halt by colliding with a seed particle. As the cluster grows under constant Reynolds
 5 number, particle detachment is further impaired by the lower drag and lift forces induced by
 6 flow shielding of neighboring particles (Derksen & Larsen, 2011). On some occasions, we even
 7 observed remaining fractions slightly overshooting unity. This occurs because the number of
 8 downstream particles accumulating near a seed particle may exceed those carried away from
 9 the camera's field of view.



10 **Fig. 5:** Monolayer bed of particles in equilibrium obtained under constant Reynolds number
 11 (Re). The remaining fraction f_r decreases with increasing Reynolds number. The term u^* is the
 12 corresponding friction velocity. The camera images were obtained with the rough substrate S2.

13 Figure 6 shows the obtained remaining fractions $f_r(Re)$ for the smooth reference substrate S1
 14 (blue circles) and the rough substrates S2 (orange squares) and S3 (green diamonds). For
 15 comparison purposes, the data obtained with S2 and S3 are overlaid with the reference blue
 16 points.



1 **Fig. 6:** Fraction of particles remaining in the field of view (f_r) against Reynolds number (Re)
2 for the three substrates S1 (blue circles), S2 (orange squares) and S3 (green diamonds). The
3 dashed lines are best-fitted to the experimental data with a hyperbolic tangent function.

4 In Figure 6, the experimental points associated with each scenario are determined from ten
5 independent experimental runs. No selection from the raw data has been done. Overall, the
6 resuspension data obtained in the wind channel show a relatively good reproducibility.
7 Irrespective of the substrate, the remaining fractions starts to decrease a $Re \approx 2000$. Beyond
8 $Re > 8000$, all particles have left the camera field of view. The previously mentioned
9 overshooting behavior with punctual values of the remaining fraction greater than unity are also
10 seen in Figure 6.

11 To determine the threshold Reynolds number $Re_{0.5}$, the experimental data are fitted with a
12 smooth hyperbolic tangent function of the form

$$f_r(Re) = \frac{1}{2} \left[1 - \tanh \left(\frac{Re - Re_{0.5}}{\Delta Re} \right) \right]. \quad (3)$$

13 The above formulation, which has been suggested by Barth et al. (2014), has advantages. First,
14 the threshold $Re_{0.5}$ is directly included in the function. Second, the denominator ΔRe in
15 Equation (3) relates to the slope of the curve at the ordinate position $f_r = 0.5$. It hence provides
16 a good indication about the scattering, that is the velocity range over which resuspension occurs.
17 In the limit $\Delta Re \rightarrow 0$, f_r converges to the step function and resuspension becomes a sudden
18 process similar to that described in Shao and Lu (2000) for wind erosion and would be, in
19 essence, much reminiscent of the Shields theory frequently used for sediment erosion in watery
20 flows (Paphitis, 2001). We find that, with the substrates S1, S2 and S3, half of the particles
21 resuspend at a threshold Reynolds number $Re_{0.5} = 2809, 3055$ and 2657 , respectively. The
22 equivalent threshold velocities are $U_{0.5} = 4.10, 4.46$ and $3.88 \text{ m}\cdot\text{s}^{-1}$. These three thresholds are
23 close to one another, which is consistent with our median adhesion force measurements. We
24 also find $\Delta Re = 925, 1285$ and 777 , which respectively converts to velocity denominators ΔU
25 $= 1.35, 1.88$ and $1.13 \text{ m}\cdot\text{s}^{-1}$. These three measures of the scattering are also relatively close to
26 one another. A closer look at Figure 6, especially in the region $Re > 5000$, shows however a
27 higher frequency of nonzero remaining fractions for the rough substrates S2 and S3 compared
28 to the smooth substrate S1. In fact, with the exception of only a few experimental points, all
29 particles are already resuspended from the smooth surface S1 in this upper Reynolds number
30 region. This trend can be related to the higher probability of finding particles with large
31 adhesion forces in S2 and S3. In Figure 4b, the corresponding 75th percentiles are about three

1 times as large as the maximum adhesion force measured for the smooth substrate S1. Such
 2 strongly adhering particles are potential candidates acting as seed particles, trapping other
 3 particles colliding with them on the surface and triggering cluster formation as shown in Figure
 4 5. In addition, the IQRs in S2 and S3 are also larger than in S1. This leads to a higher variability
 5 in the remaining fractions. See, for instance, the larger spread of green points at fixed Reynolds
 6 numbers in Figure 6. We hence can relate particle resuspension at high Reynolds number to the
 7 tail of the adhesion force distribution, for which the 75th and 90th percentiles are representative.
 8 This confirms our former idea (Henry & Minier, 2018), that statistical information related to
 9 the adhesion forces should ideally contain more than the average and the standard deviation for
 10 an accurate prediction of the resuspension fraction. Here, our measured adhesion force
 11 distributions are clearly not Gaussian but multimodal.

12 **3.3. Comparisons of the threshold velocity with literature data**

13 For comparison purposes, the hyperbolic fits are also shown with selected experimental data
 14 taken from other sources. In the aerosol community, the remaining fraction is commonly plotted
 15 as a function of the friction velocity (u^*) calculated at the wall. To estimate it, an empirical
 16 correlation with an accuracy of about 5 % under fully developed turbulence is presently used
 17 (Hartnett, Koh, & McComas, 1962; Jones, 1976). By defining the friction factor as $f =$
 18 $8(u^*/U)^2$, we solve the modified Kármán–Prandtl equation given by

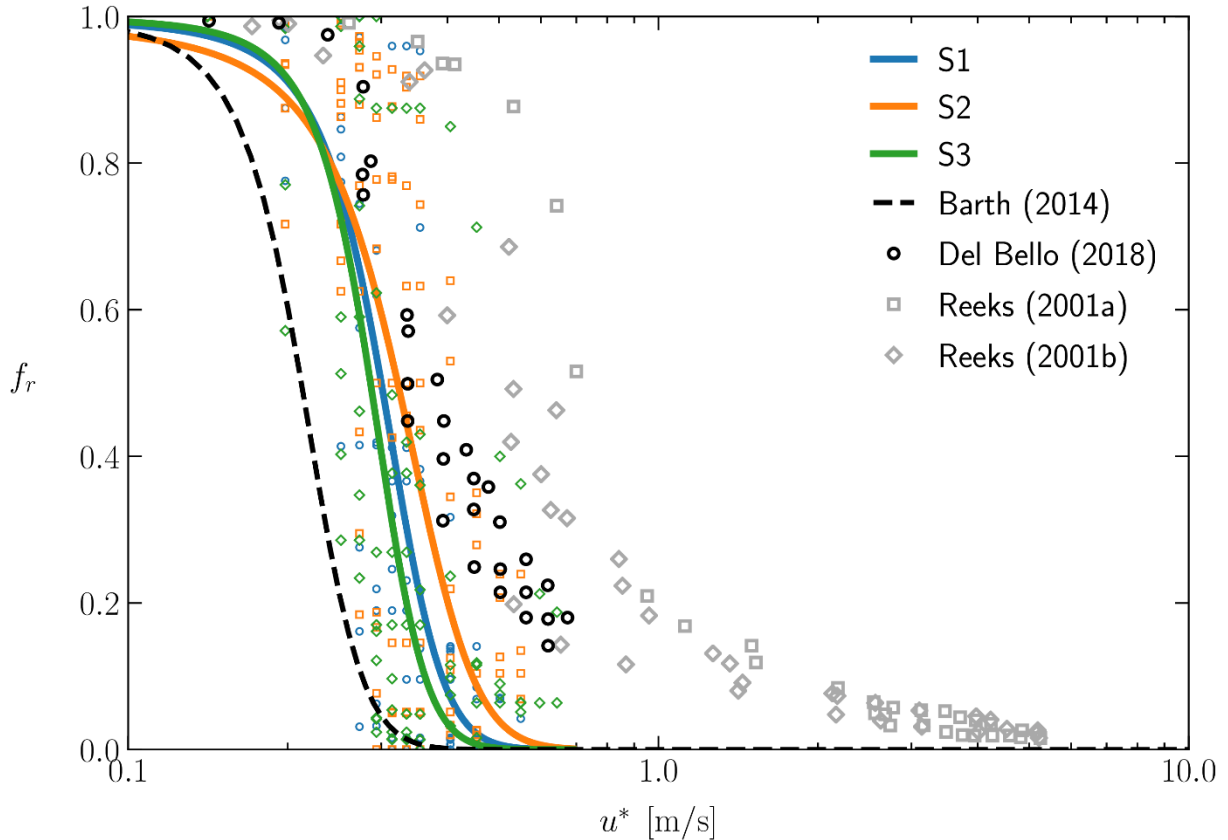
$$\frac{1}{\sqrt{f}} = 2 \log_{10}(\beta Re \sqrt{f}) - 0.8, \quad (4)$$

19 where $\beta = 1.125$ is a correction coefficient introduced to account for the square cross-section
 20 of the channel. We are well aware, that Equation (4) is only valid for smooth channels and
 21 $Re > 4300$. Present experimental observations show that resuspension mostly occurs for
 22 Reynolds number ranging from 2000 to 6000. Favoring a continuous function linking the
 23 Reynolds number to the friction velocity, the formulation applicable to the laminar and
 24 intermediate regimes is here left out. Using Equation (4) outside its range of validity does not
 25 change the following analysis. Authors interested in using our data, for instance to validate their
 26 model, are encouraged to use the Reynolds number. Figure 7 compares our results to literature
 27 data. Barth et al. (2014) used 20- μm glass spheres and a steel plate with sub-micrometer
 28 roughness, Reeks and Hall (2001) 10- μm alumina spheres (labeled as 2001a), 20- μm alumina
 29 spheres (labeled as 2001b) and a polished stainless-steel substrate, Del Bello et al. (2018) ash
 30 particles with diameter ranging from 125 to 250 μm and a substrate with wall roughness in the
 31 same order as the particle size. The above data are charted in Figure 7 with a logarithmic scale
 32 on the abscissa for better illustration. The remaining fractions obtained with the present smooth
 33 and rough substrates compare well with those from other studies. In Figure 7, the threshold
 34 velocity ($u_{0.5}^*$) determined by other authors varies between 0.2 $\text{m}\cdot\text{s}^{-1}$ to 0.6 $\text{m}\cdot\text{s}^{-1}$. The present
 35 threshold velocities are equal to 0.30, 0.32 and 0.28 $\text{m}\cdot\text{s}^{-1}$ for S1, S2 and S3.

36 **3.4. Potential limitations of this study**

37 This study slightly differs from others. In Barth et al. (2014), the substrates from which the
 38 spherical particles resuspended, were made of steel. The Young's modulus of steel is much
 39 greater than that of the functionalized coating, here made of resin (see section 2.3). The
 40 roughness asperities likely deform, which might make it difficult to estimate the number
 41 contacts between a particle and the rough substrate. The spheres exhibit some roughness too.

1 In addition, individual damaged asperities were also observed with every experiment. We hence
 2 limited the number of runs per substrate in the wind channel to ten. The adhesion force is
 3 dependent on the ambient atmospheric conditions. Despite doing our best minimize these
 4 adverse effects, the measurements with the AFM and in the wind channel were performed
 5 separately and had to be made at different times and locations. Finally, the AFM measurements
 6 are done on a rather small surface, typically in the order of 10^{-2} mm². The remaining fractions
 7 are rather integral values obtained from a much larger wall surface, typically a few square
 8 millimeters (mm²).



9 **Fig. 7:** Comparison of the fraction of remaining particles (f_r) against the friction velocity (u^*)
 10 with literature data.

11 Conclusions

12 The resuspension of glass particles with a 100- μ m diameter exposed to a turbulent gas flow
 13 was studied at Reynolds number up to 8000. Our measurements include adhesion force and
 14 remaining fractions against increasing gas velocity. Three substrates were used, namely a
 15 smooth and two artificially roughened ones. Three main messages emerge from our study and
 16 further stress the importance of using well-defined asperities rather than a manually abraded
 17 surface.

- 18 • The chaotic nature of a manually abraded surfaces, in terms of highly heterogenous asperity
 19 size, shape and spatial distribution, is responsible for the lack of correlation between surface
 20 roughness and threshold velocity. To highlight this, we briefly recall previous experimental
 21 results (Barth et al., 2014; Jiang et al., 2008). In those works, steel substrates with increasing
 22 wall roughness were used. The curves $f_r(u^*)$ did not necessarily lead to the conclusion that

1 an increase in wall roughness was associated with a lower threshold velocity $u_{0.5}^*$. With
2 identical spherical beads, the threshold velocities were often close to one another irrespective
3 of the wall roughness and in some cases, an increase in the threshold velocity was even
4 reported for higher roughness.

- 5 • Our results obtained with functionalized wall surfaces, that are roughened with well-defined
6 microasperities, do behave as expected (Audry, Ramos, & Charlaix, 2009; Tormoen et al.,
7 2005). Compared to the reference scenario S1 exhibiting a roughness profile in the
8 nanoscale, the microasperities in S2 and S3 lead to a larger scattering in the adhesion forces
9 and the friction velocities. How the adhesion force distribution relates to surface roughness
10 depends on the particle diameter, the roughness size along with the deformability of the
11 particle and substrate, as this determines the number of asperities in contact with the particle.
- 12 • Our measurements of the adhesion force distribution and resuspension fraction as a function
13 of the Reynolds number can be used for future model development and validation. Our
14 experiments are motivated by theories of contact mechanics and state-of-the-art simulations
15 modelling asperities as spherical caps (Guingo & Minier, 2008; Henry & Minier, 2014b). In
16 this context, we have experimentally explored particle resuspension from wall surfaces
17 functionalized with well-defined roughness elements, which could be used in simulations.

18 **Acknowledgements**

19 This work was funded by the Helmholtz Associations Initiative and Networking Fund within
20 the frames of the Helmholtz Climate Initiative (HI-CAM), the Helmholtz project CORAERO
21 and the Helmholtz Innovation Lab, Clean Water Technology (CLEWATEC). Funding by the
22 European Social Fund and the Free State of Saxony (Grant Number 100284305) is also
23 acknowledged.

24 **Author contributions**

25 A.B. and G.L. conceptualized and designed the study. A.B., G.L. and E.M. performed the wind
26 channel experiments. K.G. and M.R. performed the adhesion force measurements. P.L. and
27 K.Z. prepared the substrates by functionalizing their surfaces. R.H. performed the SEM image
28 analysis of the substrates and particles. C.H. made a significant contribution to the discussions.
29 C.H., M.B. and U.H. aided in interpreting the results. G.L. and U.H. contributed to the
30 acquisition of the financial support for this work. All authors discussed the results and reviewed
31 the manuscript.

32 **Data availability**

33 All raw data used in this work have been made available with a DOI number (Gregory.
34 Lecrivain, 2023).

35 **Highlights**

- 36 • Surface functionalization is used to fabricate wall surfaces with well-defined asperities
37 represented by cylindrical micropillars and microcubes.

- 1 • The resuspension of glass particles with a 100- μm diameter exposed to a turbulent gas flow
2 was studied at Reynolds number up to 8000.
- 3 • The response of the manufactured surfaces in relation to adhesion force distribution and
4 threshold friction velocity, at which 50 % of the particles resuspend, is examined.
- 5 • The well-defined microasperities have little to moderate effect on the median adhesion force
6 and the threshold velocity. The data scattering is however much more affected.

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