FORCE OF ADHESION BETWEEN PARTICLES AND A SURFACE

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Abstract. The determination of the adhesion force between particles and surfaces is a very important parameter to be studied and determined because it is of great interest to an extensive range of industrial operations, as in filtration, in coating of surfaces and in the food and pharmaceutical industry. For instance, in the pharmaceutical industry, undesired adhesions can favor the accumulation of residues on the surface of the tablets, thus seriously affecting equipment performance. There are many variables that influence the mechanism of the adhesion; however research specifically dedicated to particle adhesion smaller than 50 µm is scarce. This work aims at investigating the influence of the size of dust particles on the force of adhesion between particles and a surface using the centrifugal technique at different compression speeds and detachment. An equation to correlate the experimental results obtained for two inorganic powdery materials and an organic one is proposed. The particle diameter ranges studied were 5 - 10 µm, 10 - 15 µm, 15 - 20 µm, 20 - 25 µm and 25 - 30 µm. The centrifuge used in the experiments was at maximum speed rotation of 14000 rpm. An image analysis program (Image-Pro Plus 3.0) was used to monitor, the number of stuck and loosened particles on the surface of the substratum after each angular speed increase. In the case of polydisperse particles stuck to a surface, the necessary force to separate the particles varies proportionally to size. It was verified that adhesion force between the particles of the powdery material and the surface of the substratum increases with the increase of particle size and with compression speed.

Keywords: Force of adhesion, Centrifugal Technique, Press-on, Spin-off.

1. Introduction

Particle adhesion results from the force that exists between particles and a solid surface, taking into account that the very solid surface may be the particle surface.

To know the force of adhesion is not only important for quantitative description of filtration but also for many technological processes. Better comprehension of adhesive interaction can contribute towards knowledge of phenomena such as friction, lubrication and equipment wear down (Bowden e Tabor; 1950). That is the reason why so much theoretical and experimental work is being dedicated to problems of adhesion, as revised by Kordecki and Orr (1960), Corn (1966), Krupp (1967), Zimon (1982) and Lee et al. (1988).

In various industrial processes adhesion can generate undesirable effects, as for example in filtration and drying, among others (Weiner et al. 1988). It can also promote contamination of microcomputer “chips” and optic-sensitive surfaces (Lam e Newton, 1991). In cleaning processes of fabric filters (solid gas separation filters), adhesion can increase the quantity of particled material retained in the filtering means (cloth or felt) after consecutive cleaning cycles, thus diminishing filtration cycle time. In the food and medicament industry it can cause efficiency reduction in industrial operational processes.

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For example, in drying processes or in machines that fill medicine capsules, repeated contact with the metallic parts of the equipment leads to the build up of dust particle layers on the metal, which could seriously affect the performance of such machines (Siegel et al., 1963). However, in many instances this adhesion is desirable, as for example in compacting and particle coating and surface operations.

For the most part, adhesive strength among adjacent particles and between particles and a surface are due to Van der Waals forces, electrostatic and capillarity, yet predominance of one or many at the same time depends on environmental conditions during the experiments and on physical-chemistry properties of the materials in contact (Podczeck et al. 1996). However, adhesive strength is acknowledged as a sum of various forces and is illustrated by Equation (1).

\[ F_{ad} = F_{vdw} + F_e + F_c \]  

(1)

Being, \( F_{vdw} \) Van der Waals force, \( F_e \) Electrostatic force and \( F_c \) Capillarity force.

There are many experimental methods and techniques that have been developed to measure adhesive strength between a particle and a surface (Krupp, 1967; Boehme et al., 1962). Among such methods the most widely used are atomic force microscopy, separation by electric field and centrifugal technique. Yet centrifugal force has an advantage of being able to determine adhesive force among real particles with regular and irregular forms in smooth or wrinkled surfaces. Moreover, it allows determining adhesive strength throughout distribution of adhesive force inside a large group of particles (containing up to 1000 particles) on a substrate, in a single measurement. For this method, adhesive strength is equal in magnitude to the required centrifugal force to separate the particles from the substrate but with opposite signal.

Based on the centrifugal technique, Banda (2002) developed an experimental methodology to determine the adhesive strength between particles and a flat surface. His results were quite satisfactory. That is the reason why this work aims at investigating the influence dusty particle size has on particle substrate adhesive strength, using the centrifugal technique developed by Banda (2002), for different compression and detachment speed. This will certainly be an important step to determine the force of adhesion among particles, an extremely significant parameter to dimension equipment such as: fabric filter, paste drying, particle coating, among others.

2. Material and Methods

2.1. Dusty Material

To perform the experiments three types of dusty material were used. Two of them were inorganic, concentrated phosphate, \( \rho_p = 3,066 \text{ g/cm}^3 \), and dolomite limestone, \( \rho_p = 2,838 \text{ g/cm}^3 \), while the other one was organic, manioc starch (\( \rho_p = 1,491 \text{ g/cm}^3 \)). The mean diameter (\( d_p \)) of the concentrated phosphate particle was of 14,91 \( \mu \text{m} \), the mean diameter of the (\( d_p \)) dolomite limestone particle was of 11,97 \( \mu \text{m} \) and manioc starch was of \( d_p = 4,93 \mu \text{m} \).
2.2. Equipment

The experimental system used was basically composed of a microcentrifuge (MA – 860, Marconi Equipamentos), a dust disperser, an optic microscope (Olympus BX60), an image analyzer (Image-Pro Plus 3.0) and a microcomputer containing the necessary software to deal with data and result analysis. Maximum speed of the microcentrifuge was of 14000 rpm. On the head of this microcentrifuge, two aluminum tubes were purposefully installed, as shown Figure 1, and whose goal was to sustain the proof disc that contained the dusty material distributed on its surface.

![Aluminum tubes installed at the head of the microcentrifuge MA – 860.](image)

**Fig. 1.** Aluminum tubes installed at the head of the microcentrifuge MA – 860.

2.3. Experimental Procedure

Determination of the adhesive strength was carried out using the Centrifuge Technique. A high rotation speed centrifuge containing the aluminum tubes was used for this function. These tubes were installed in a fixed angle rotor, in order to allow particle deposition perpendicular to the rotation axle of the centrifuge. The adapters, also built of aluminum, were inside the tubes, with the proof discs made of steel. The surface of these discs was polished. Afterwards, some meshed-shaped grooves were made on the polished surfaces where the area of each mesh was of 0,5 mm\(^2\). These squares were used as reference to locate a certain particle after each centrifuge in the optic microscope, and hence determine the centrifugal speed at which this particle was detached. Figure 2 shows a polished proof disc, exposing the reticle on its surface. Beside it one can see it amplified 100 times by the optic microscope – Olympus BX60.

![Surface of proof disc containing the reticles; A single reticle of the proof disc surface.](image)

**Fig. 2.** (a) Surface of proof disc containing the reticles; (b) A single reticle of the proof disc surface.
The relative humidity of the air was controlled and maintained below 50%. The temperature of the laboratory where the experimental batches were accomplished was maintained between 15 and 20°C.

After executing the previous stages the particles of the dusty material were put on the surface of the disc, aided with the powder dispersion system (Galai PD-10, vacuum gage), so that they would not agglomerate. The dusty surfaces of the proof discs that contained the powder material were placed in the rotor axle direction so that the centrifugal force, press-on, acted first on the particles and immediately afterwards, on the surface. The compression speed (press-on) applied on the experimental batches were of 1000, 2000 and 10000 rpm, respectively. Subsequently, the sample was taken out of the centrifuge and the particles were counted using the image analyzer (Image-Pro Plus 3.0) that was installed in the microcomputer and connected to the optic microscope Olympus BX60 (Olympus Co. Tokyo Japan), coupled to a color video camera, CCD-IRIS (Sony Co. Japan), in order to determine the number of particles adhered to the surface.

The proof discs were returned to the microcentrifuge so that the dusty surfaces were positioned to the external part of the rotor head, and in this manner the spin-off centrifugal force would act first on the surfaces and afterwards on the particles, in order to accomplish the detachment of the particles on its surfaces.

During the operation of particle detachment (application of spin-off centrifugal force), the disc was subjected to crescent rotation speeds and consequently, crescent centrifugal forces. At each step of rotational speed increase, images of the remaining particles on the discs were obtained. The centrifugal speeds (spin-off) used on the experimental batches were of 1000, 3000, 5000, 7000, 9000, 11000, 13000 and 14000 rpm.

3. Results and Discussion

For each powdery material, centrifugal force of compression was applied at 1000, 2000 and 10000 rpm. Subsequently, for each powdery material and also for each compression speed a centrifugal detachment force of 1000, 3000, 5000, 7000, 9000, 11000, 13000 and 14000 rpm. was applied.

Figure 3 shows the results gathered from one of the experimental tests, where a percentage graphic was built of adhered particles on the surface of the discs in function of the angular speed detachment of phosphate concentrate particles upon the application of compressive centrifugal speed of 2000 rpm. One can see that with the increase of angular speed, the percentage of adhered particles on the surface started to decrease until all particles were detached, after applying spin-off centrifugal force of 14000 rpm.

Using the curves shown in Figure 3 (a), the graphics of figure 3 (b) were built from the percentage of adhered particles on the surface of the discs as a function of the adhesion force for three fractions of powders. Adhesive force is calculated by equalizing the magnitude of the applied centrifugal force with the opposite sign ($F_{centrifugo} = - F_{adesão}$). The centrifugal force is represented by Equation (2).

$$F_{centrifugo} = m * w^2 * r$$  \hspace{1cm} (2)
This distance between the substrate surface and the rotation axle is of 0.057 m. The mass of phosphate concentrate was obtained by using Equation (3).

\[
m = \rho_p \ast V_p
\]  

(3)

\( m \) being the particle mass, \( \rho_p \) particle density and \( V_p \) particle volume.

Fig. 3. (a) Percentage of adhered particles on the surface of discs as a result of detachment speed for phosphate concentrate upon the application of decompression force of 2000 rpm. (b) Percentage of adhered particles on surface of discs as a function of adhesive force, for phosphatic concentrate after application of compression force of 2000 rpm.

The curves obtained in Figure 3 (b) showed a linear behavior in this coordination, this justifies that the data obeyed a log-normal distribution. The same behavior was observed for speeds of compression of 1000 and 10000 rpm as well as for the remaining powders here investigated.

For each percentage curve of adhered particles as a result of adhesive force, the mean adhesive force can be characterized (Zimon, 1982). The mean adhesive force or geometric medium can be defined with the adhesive force to which a 50% probability of the particles remained adhered to the substrate after centrifuge. This was used to show the mean force of adhesion of a particle to the substrate.

This procedure was used to determine the mean adhesive force for the five stripes of diameters of the powdery material, as can be seen in Table 1. This table also shows that the force of adhesion between particles of powdery material and the surface of the stainless steel disc increases with the size increase of the particles and with the increase of compression force (press-on).

Figure 4 shows an adhesive force diagram as a result of the mean diameter of particles of the three powdery materials used in the experiments, after applying centrifugal speed compression (press-on) of 10000 rpm. It can be observed that for the same applied speed compression, the organic powdery material (manioc starch) showed the strongest adhesive force in relation to the inorganic powdery material (dolomite limestone and phosphate concentrate). Also, the adhesive force of the particles of the three materials used in the experiments increased with the size increase of the particles on the surface of the stainless steel disc. The same behavior was seen for compression speeds of 1000 and 2000 rpm.
As can be seen in Figure 4 (a), the difference of adhesive force among the three powdery materials can be explained by the physical characteristics of the particles. The particles of the inorganic powder (phosphate concentrate, sphericity of 0.60 and of dolomite limestone, sphericity of 0.64) show very irregular shapes, practically the same granulometric distribution and very similar values of density, while the particles of organic powder (manioc starch, sphericity of 0.94) have more regular shapes, close to a sphere, less density and a lesser stripe of granulometric distribution, as verified in Figure 4 (b), which shows granulometric distribution for the three powdery materials.

According to Corn (1961), for hard materials and clean surfaces, a useful empirical expression for adhesive force based on direct measurement for glass and quartz particles (> 20 µm) at 25 °C, is represented by Equation (4):

\[ F_{\text{adhesion}} = 0.063 \times d \times [1 + 0.009 \times (%\text{RH})] \]  

Based on Equation (4), an equation that would better relate the experimental results obtained was put to the test in this work. Since the relative humidity of the air was constantly maintained at 39%, throughout all experiments, Equation (4) can be represented by Equation (5):

\[ F_{\text{adesão}} = k \times d \]
Table 1. Comparison of Geometric Medium, of Adhesive Force for the three materials upon the centrifugal force application of compression (press-on) of 1000, 2000 and 10000 rpm.

<table>
<thead>
<tr>
<th>Powdery Material</th>
<th>Press-on</th>
<th>Average Diameter (µm)</th>
<th>Adhesion Force ($\times 10^8$ N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powdery Material</td>
<td>1000 rpm</td>
<td>6.50 12.48 17.91 21.79 26.75 6.55 12.50</td>
<td>9.88 24.97 42.99 54.40 63.97 29.69 53.48</td>
</tr>
<tr>
<td>2000 rpm</td>
<td>16.83 22.82 26.62 6.68 12.11</td>
<td>82.80 117.77 136.20 39.03 83.70</td>
<td></td>
</tr>
<tr>
<td>10000 rpm</td>
<td>16.95 22.44 28.25</td>
<td>108.97 152.73 186.97</td>
<td></td>
</tr>
<tr>
<td>Manioc Starch</td>
<td>1000 rpm</td>
<td>6.52 12.53 17.20 22.27 27.14 7.07 11.97</td>
<td>3.41 5.90 7.64 9.37 12.10 4.97 7.08</td>
</tr>
<tr>
<td>2000 rpm</td>
<td>17.57 22.08 27.84 6.63 11.96</td>
<td>9.12 11.75 14.86 9.72 23.86</td>
<td></td>
</tr>
<tr>
<td>10000 rpm</td>
<td>17.17 22.42 27.11</td>
<td>30.77 38.47 48.82</td>
<td></td>
</tr>
<tr>
<td>Dolomite Limestone</td>
<td>1000 rpm</td>
<td>6.69 12.10 17.20 22.39 26.72 6.92 12.07</td>
<td>2.86 5.41 6.99 8.08 8.79 4.59 6.66</td>
</tr>
<tr>
<td>2000 rpm</td>
<td>17.29 22.57 27.29 7.39 12.26</td>
<td>8.59 10.43 12.83 8.28 17.25</td>
<td></td>
</tr>
<tr>
<td>10000 rpm</td>
<td>16.72 22.51 27.55</td>
<td>22.53 27.57 35.97</td>
<td></td>
</tr>
</tbody>
</table>
Where $k$ is a constant, whose value is included in the relative humidity of the air and the chemical characteristics of the powdery materials, and $d$ is the diameter of the particle, in meters.

The graph in Figure 5 indicates the adhesive force of the manioc starch as a function of its mean particle diameter upon the application of an angular compressive speed of 1,000, 2,000 and 10,000 rpm. One can see in this figure that the force of adhesion increases linearly with the diameter increase of the manioc starch particle and with the increase of the angular speed compression. The same behavior observed for the organic material in Figure 5 was verified for both inorganic materials, maintaining Equation (5).

![Graph of adhesive force as a function of particle diameter and angular compressive speed](image)

**Fig. 5.** Adhesive force as result of mean diameter of manioc starch particles after applying centrifugal force compression of 1000, 2000 and 10000 rpm.

Figure 6 shows a graph of adhesive force of angular compressive speed of dolomite limestone particles after applying angular compressive speed of 1000, 2000 and 10000 rpm.

It was seen that adhesive force increases in a non-linear manner with the increase of angular compressive speed on the particles of phosphatic concentrate, dolomite limestone and manioc starch. The equation that best adjusted to the results was Equation (6):

$$ F_{\text{adhere}} = k \cdot \omega^\alpha $$

(6)

For the phosphatic concentrate, dolomite limestone and manioc starch, the exponent $\alpha$ was of 0.6, 0.7 and 0.3, respectively for all the particle diameter stripes.
Analyzing Figures 5 and 6 it was possible to conceive how an adhesive force varies with the mean diameter of the particle and with the angular speed of compression.

One can see that for all materials studied, the variation of the adhesive force with the mean diameter of the particle is similar to Equation (4) as proposed by Corn (1961).

Using the experimental results obtained in this work, an equation that could represent more extensively the experimental results obtained for the three powdery materials were proposed. Hence, Equation (7) best represented the adhesive force and a stainless steel surface among particles of the three powdery materials, for a constant relative humidity of the air.

\[ F_{\text{adhesion}} = k \times d \times \omega^\alpha \] (7)

With \( k \) being a constant, whose value is embedded in the relative humidity of the air, the sphericity of the particle and the chemical and physical characteristics of the powdery materials, \( \alpha \) is the parameter of the equation, \( d \) is the particle diameter, it is in meters and \( \omega \) is the angular speed of compression, whose unit is \( s^{-1} \).

4. Conclusions

The adhesive force among the particles of the three materials and the surface of the stainless steel disc increased with the increase of the particle sizes and with the increase of the compression speed (Press-on).

Particle diameter dependency on the adhesive force increased with the spherical increase of the powdery material. Adhesive force increases in a non-linear manner with the increase of angular compressive speed on the particles of phosphatic concentrate, dolomite limestone and manioc starch.
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Acknowledgments

The authors would like to express their gratitude to CAPES for financial support.