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Food Powders Properties and Characterization

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Food Powders Properties and Characterization

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Preface

Due to recent developments and progress in food powder technology and significant advancement in the analytical and processing possibilities, there has been a gap in the literature in this field. For this reason, we would like to introduce *Food Powders Properties and Characterization* with a great pleasure to our respected readers. The students, industrialists, and researchers studying or dealing with food powders may benefit from this book which presents the fundamental properties of food powders and methods of characterization. The chapters include relevant aspects of particle properties as well as bulk powder properties. The main focus of this book was to give a comprehensive overview of powder characterization and an insight into recent research work related to food powders.

In this book, the physical and chemical properties of food powders and their effect on food powder behaviour are discussed. In addition, some chapters were focused on particle properties, modification of particles, caking–anticaking mechanisms, powder from fruit waste, and microbiological assessment of food powders. We have also included a chapter about rehydration behaviour of food powders which particularly have high protein content. We hope that this book will help to fill the knowledge gap in the literature.

We are very grateful to Springer Nature for their valuable guidance and cooperation. I would like to thank all authors for agreeing to be a part of this book project.

Istanbul, Turkey — Ertan Ermiş
April 2020

Contents

Chapter 3
Adhesion of Food Powders

Ertan Ermiş

3.1 Introduction

In food industry, particle adhesion and cohesion has particular importance in many applications such as coating with powders, dosing of powders, surface cleaning of the process equipment, discharge from the storage units, mixing/blending, packaging and new product development. Therefore, control of adhesion and cohesion forces in food powders is essential to design the processes and to improve the process efficiency.

Adhesion is the state in which a powder particle held on a solid surface by different interfacial forces (i.e. van der Waals, electrostatic and capillary forces) and mechanical interlocking action, while cohesion describes the affinity of one particle to another. Adhesion can be managed by controlling numerous factors such as particle size, shape, surface morphology, moisture content and chemical composition.

While the adhesion of particulates or soft solids on surfaces is desired in some food applications, adhesion of unwanted material and their accumulation to form fouling deposits is not wanted in some processing stages. This unwanted adhesion may reduce process efficiency and lower product quality as well as compromising hygiene and may result in cross-contamination.

Different techniques have been developed to apply powder coating onto the surfaces. Since the adhesion of particles on the surfaces is not well understood, various methods have been studied to determine the adhesion or removal behaviour of food powders on surfaces. In this chapter, the adhesion of food powders, the recent developments in determination of particle adhesion and evaluation of the performance of the test methods developed are given.

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3.2 Adhesion of Food Powders

The adhesion can be defined as the attraction between two solid material having a common contact surface which is produced by intermolecular attractive forces within short distances (Petean and Aguiar 2015). Adhesion plays an important role in many applications such as powder coating and processing of cohesive powders. Powder coating refers to the adhesion of food powder onto the surface of food products (Ermis et al. 2011). Seasoning powders are often added to improve the appearance and taste of the food products. Adhesion of seasonings to snack foods should be consistent and to obtain uniform and even distribution of seasonings on the surfaces, most manufacturers apply excess coating powder. This may lead to fugitive build-up on the surfaces of processing equipment and this may result in giving break in production for cleaning of the processing equipment (Adhikari et al. 2001; Ermis et al. 2011). The powder might become lumpy over the equilibrium moisture and temperature especially for milk and fruit powders due to the existence of low molecular weight sugars in high concentration (i.e. glucose, fructose, and sucrose) (Adhikari et al. 2001).

For most of the snack foods, seasonings are applied together with oil or immediately after frying process. It has been reported that increasing surface oil content resulted in increase of adhesion (Enggalhardjo and Narsimhan 2005). Studying adhesion mechanisms and measuring of the adhesive force is needed to better understand the powder behavior to diminish powder waste and to increase efficiency in powder coating processes (Zafar et al. 2014).

Numerous factors such as flowability, relative humidity, particle size and particle shape can influence the adhesion of powders to the surfaces. The flowability and dispersibility of fine powders usually become poor when particle-particle and particle-surface adhesion strength is increasing (Zafar et al. 2014). Powder flowability is affected by particle size (Teunou et al. 1999). In general small particles having high surface to volume ratio are more cohesive with poor flowability. Free-flowing powders are preferred for uniform (evenly dispersed) powder coating (Khan et al. 2012). Powder with free-flowing property increase the transfer efficiency and dispersion over the food substrate surface. However, cohesive powders may produce better adhesion due to higher percent side coverage on the target surface (Sumawi and Barringer 2005).

It has been reported that particle size has remarkable effect on adhesion strength and wrap-around effect (percent side coverage) during coating because of stronger van der Waals forces per unit of mass (Halim and Barringer 2007; Buck and Barringer 2007; Ermis et al. 2011). As the particle size increases, the percent side coverage decreases and hence weaker adhesion occurs between particle and surface due to lower charge-to-mass ratio (Halim and Barringer 2007). Attention has been paid to adhesion properties of fine particles in process engineering due to the fact that those properties may cause unwanted effects such as blockage, detachment or poor flowability leading to reduced efficiency in production processes (Adhikari et al. 2001). Adhesion of fine particles to surfaces is closely relateds to industrial hygiene and air pollution (Petean and Aguiar 2015).

Particle shape and the surface area of particles are other factors affecting adhesion to surfaces (Karasu and Ermis 2019; Buck and Barringer 2007; Nussinovitch 2017). It has been reported that flake shaped particles adhere better than cubic and dendritic shaped ones, particularly for bigger particles than 200 μm (Miller and Barringer 2002; Niman 2000). In addition, chemical composition, moisture content and water activity of both powder material and substrate are affecting adhesion. One of the most important factors affecting particle adhesion is surface oil/liquid content. The effectiveness of coating increased with increasing oil content (Miller and Barringer 2002). The type of oil and it's composition affects adhesion behaviour of food powders due to the differences in viscosities (Enggalhardjo and Narsimhan 2005). The surface topology, porosity and roughness are also other factors affecting adhesion of particulates. If the particle size is smaller than the pore size of the surface, mechanical interlocking may take place (Bowling 1988). Substrate temperature is reported as another factor affecting adhesion of food powders in the presence of surface oil. Decrease in surface temperature yields lower adhesion (Buck and Barringer 2007).

Adhesion of food powders in food containers and packages may affects consumers' acceptability adversely. Adhesion of food powders in packaging causes deformation of the product surface. Unwanted powder adhesion in packages may cause consumer antipathy to the product (Kilcast and Roberts 1998; Adhikari et al. 2001).

Various methods have been used in coating food substrates (i.e. snack food) with powder materials such as seasoning powders. Tumble drum and conveyor belt techniques are the most common methods for seasoning coating. Another emerging technique, electrostatic powder coating is one of those methods which can be applied in industrial applications (Halim and Barringer 2007). In this method, powder particles form a powder cloud and disperse evenly on the food surface by applying electrostatic forces which result in attraction between charged particles and food surfaces due to the high charge-to-mass ratio of the small particles (Halim and Barringer 2015). Electrostatic powder coating was reported as a promising technique for smaller size fractions (particularly below 100 μm) when there is no oil or liquid on the surface of the substrate (Buck and Barringer 2007).

To better understand the behaviour of food powders, the adhesion forces and factors affecting adhesion need to be studied in detail. Several experimental, theoretical and numerical studies have been carried out to measure and to better understand the particle adhesion (Zafar et al. 2014).

3.3 Powder Coating Systems

Coating with food powder involves the application of particulates on the surface of food product to achieve new functionalities such as improving sensory attributes (i.e. color and flavour) for increased consumer acceptability; improving nutritional quality (i.e. application of vitamins, mineral sor bioactives); improving flowability by applying anticaking agents (e.g. powdered cellulose on graded cheese) or to coat with antimicrobial agents for enhancing shelf-life (Dhanalakshmi et al. 2011; Yousuf and Barringer 2007; Khan et al. 2012; Elayedath and Barringer 2002). Therefore, effective targeting of coating material and even distribution of powder particles on the surface of the food product is desired in food industry (Khan et al. 2012). Powder coating should be done properly to spread the coating material across the target evenly with high transfer efficiency. The adhesion of powder material is very important to keep the particles on the food surfaces. To fixate powder particles to the product surface, oil or hydrocolloid solutions first sprayed on the target surface to promote adhesion of particles.

3.3.1 Coating in the Gravity Drum (Tumble Drum Coating System)

Tumble drum coating is a common and widely used method to apply coating if the food product can be tumbled (Biehl and Barringer 2003). Tumble drums are horizontal cylinders with a degree of inclination to allow product flows from one end to the other (Hui 2006). They are designed in a way to create folding-in action which cascades down the surface of the food products. The seasoning particles are carried in a direction opposite the cascading layer (Denis et al. 2003). Uniform distribution of the flavouring powder is achieved by exposing the entire base product to the flavour spray or powder application within the coating zone while mixing the food product as a result of tumbling action (Elayedath and Barringer 2002). Powder density and feed rate of powder and the volume of the food product in the tumble mixer and the rotational speed affects coating efficiency (Wong et al. 2005). In most of the cases, a liquid media such as oil is sprayed onto the product in the tumbler to help the food powder adhere to the surfaces (Ermis 2011).

3.3.2 Belt System

The belt coating systems are in general facilitate single-side coating of products like salted crisps, crackers or pretzels (Dreier 1991). Different types of conveyor can be used such as vibratory, open wire belt, closed fabric belt, or other selected types. In this method, a given amount of powder is applied on the conveyor belt entering the coating zone. In this method, products need to be turned around when coated on a conveyer belt to evenly distribute the powder material across the target surface (Lusas and Lloyd 2001; Riaz 2015). However, coating all sides of a three-dimensional product uniformly is challenging when this technique is used. The coating efficiency, which can be defined as the amount of powder that adheres to the target compared to the total mass of powder, is relatively low in this method. Therefore, more powder material is used than the required amount to achieve desired coating efficiency (Khan et al. 2012).

3.3.3 Electrostatic Coating

Electrostatic powder coating technique uses electrostatic charges to improve the adhesion strength of powder particles onto the food substrates. A high voltage electrode attached corona gun is used to apply an electrical charge to the powder material dispersed or blowed over the surface of the substrate to be coated (Fig. 3.1). High voltage electrode generates an electric field and produce negative charges towards the particles. The grounded substrate attracts the charged particles (Khan et al. 2012).

It has been reported that this technique improves efficiency of particle coating. Since the applicator is sealed, there is no powder loss to the environment which result in reducing wastage. It has been reported that 20% less oil is needed for adhesion when using electrostatics and increasing relative humidity reduces electrostatic adhesion (Khan et al. 2012).

3.3.4 Atmospheric Plasma Coating System

Atmospheric pressure plasma discharge has been used in powder coating to the surfaces in different industries such as ceramic and automotive. The radicals, ions and active molecules are produced from a gas feed by applying high voltage of electricity. Those active molecules, ions and free radicals activate the surface of the

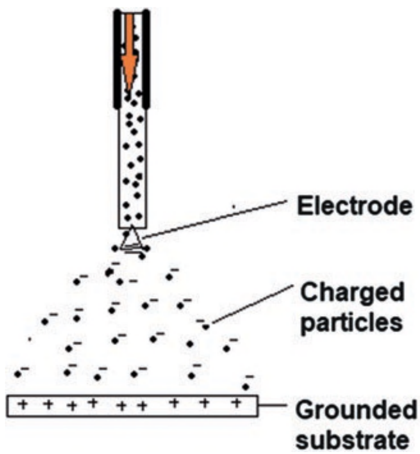

Fig. 3.1 Schematic view of electrostatic powder coating [Adapted from Prasad et al. 2016]

substrate and the particle to enhance the adhesion of powder material to the surface of the substrate. Even though there have been some researchers studying the effect of plasma discharge on food powder coating (Suganya et al. 2018), there is still a lack of information in this field.

3.4 Adhesion Mechanisms

The adhesion mechanisms and the type of adhesion forces between the particle-surface vary depending on the chemical and physical properties of solid material building the surface and particles and existence of any liquid layer between the solid surfaces. The liquid layer (i.e. oil or hydrocolloid solution) improves the interaction between liquid and soluable solids which promotes adhesion. The chemical composition and molecular structure plays an important role in adhesion behaviour. Depending on the chemical composition and molecular structure, food materials show different properties such as hygroscopic and hydrophobic properties. Based on these behaviours, food materials can be divided into three groups. These are amorphous, crystalline and semi-crystalline materials. Most of the food powders show hydroscopic (water soluable) behaviour. Some foods which are rich in fats and oils may behave as hydrophobic. (Dopfer et al. 2013). Particle shape, particle size and contact geometry affect the magnitude of adhesion force measured. For fine particles (roughly 1–10 micron), attractive surface forces dominates over inertial forces (increase in surface charge to mass ratio) and this increases adhesion of particles (Wanka et al. 2013).

Different adhesion mechanisms take place between the particle and the surface of food materials depending on the chemical composition and structure (Fig. 3.2).

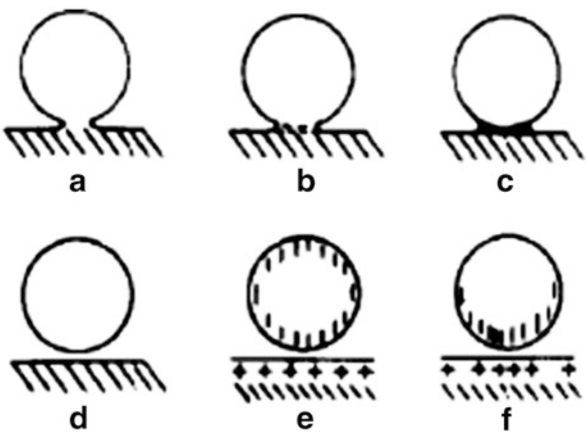

Fig. 3.2 Adhesion mechanisms between a particle and a surface. a-chemical bonding (sintering), b-bonding by crystallised solute, c- capillary forces or liquid bridge (viscous bonding), d-van der Waals forces, e and f-electrostatic forces [adapted from Schubert 1987]

The total adhesion force is assumed to be the sum of van der Waals, F_{vdw} (significant for fine powders), capillary, F_{cap} (dominant when there is a liquid layer) and electrostatic, F_{el}, (dominant when the particles are highly charged) forces among others (Ermis et al. 2011; Zafar et al. 2014; Salazar-Banda et al. 2007). Van der Waals forces increase as particle size decreases. The sum of these forces can be assumed as total adhesion force (Salazar-Banda et al. 2007):

$$F_{ad} = F_{vdW} + F_{cap} + F_{el} \tag{3.1}$$

The adhesion force between particles and between particles and surfaces is usually due to van der Waals interactions if the powder and surface are dry and without any chemical bonds and electric field (Salazar-Banda et al. 2007). It has been reported that the electrostatic forces are much smaller than the force of van der Waals if there is an compression force acting on the particle (Petean and Aguiar 2015).

Particle size has a significant influence on the cohesive and adhesive strength of a particulate system. Due to high surface to volume ratio of micro and nano-particles, they are highly susceptible to electrostatic or molecular interactions while van der Waals forces become significant below 10 micron size (Rumpf and Knepper 1962). Powders having the median particle size over 200 micron are considered as free-flowing and finer particles tend to stick together and show poor flowability due to cohesion (Teunou et al. 1999). For particles below 1 micron size, deformation may occur due to molecular forces and this leads to increase contact area which result in more intimate contact (Cyprien and Ludwik 1999). Adhesion mechanisms of particles have been studied previously and reviews have been reported in detail (Bowling 1988; Kendall and Stainton 2001; Kumar et al. 2013; Schubert 1987; Adhikari et al. 2001).

3.4.1 Electrostatic Forces

When electrically nonconducting particles come in contact, they are attributable to different contact potential values. When particles possess excess opposing charges, electrostatic adhesion may take place (Schubert 1987). The electrostatic adhesion forces for a nonconducting particle, F_{el} can be calculated using Coulomb's law as:

$$F_{el} = \frac{\pi q_1 q_2 d_1^2 d_2^2}{\varepsilon_r \varepsilon \left(d_1 + d_2 + 2x\right)} \tag{3.2}$$

where q_1 and q_2 are the electric charges of the spherical particles (Coulomb.m^{-2}), εr is relative dielectric constant (dimensionless) and ε is absolute dielectric constant (Coulomb2.N1.m^{-2}) of the surrounding medium, x (m) is the distance of separation between the particles. d_1 and d_2 are diameters of the spheres (Schubert 1987).

For electrically conducting particles, the adhesion force, F_{el} attributable to contact potential between two rigid spheres is given by:

$$F_{el} = \frac{\pi \varepsilon_r \varepsilon U^2 d_1 d_2}{2(d_1 + d_2)x} \tag{3.3}$$

where, F_{el} is force of cohesion/adhesion between the two spherical particles or between a sphere and a plane, U is contact potential (N.m.s^{-1} or volt) (varies between 0.1 and 0.7 V) (Schubert 1987).

3.4.2 Van der Waals Forces

Van der Waals forces (F_{vdW}) are generated by molecules positioned in close contact distances. These forces are kind of electrostatic forces generated as a result of temporary load shifts of the molecules due to plastic or visco-elastic deformation of particles. Lifshitz (1955) and Hamaker (1937) linked these forces to the contact zone characteristics between two surfaces of circular plates (see Eq. (x)) (Dopfer et al. 2013).

Lifhitz:

$$F_{vdW} = \frac{h\overline{w}}{32\pi h_s^3} x^2 \tag{3.4}$$

Hamaker (for $h_s < 150$ nm):

$$F_{vdW} = \frac{H}{24 h_s^3} x^2 \tag{3.5}$$

x is the diameter of the circular contact area of the two particles, h_s is the separation distance between the two particles or parallel surfaces. $h \cdot \varpi$ is the Lifshitz–Van der Waals constant (10^{-20}– 10^{-18} J) and H is the Hamaker constant which depends on the materials in contact and surrounding liquid ($10^{-19} - 10^{-18}$ J).

The distance between the particles and the contact area strongly affect the vdW forces. An increase in contact area and/or a decrease in the distance between their surfaces increases vdW forces. The changes in these geometrical properties are linked to the degree of plastic and visco-elastic deformation of the particles which are depending on mechanical particle properties (i.e. viscosity and elasticity) (Dopfer et al. 2013). Physico-chemical properties of amorphous water-soluble powder materials (i.e. maltodextrin) are affected by the concentration of water. Migration of water into the structure of an amorphous particle may lead to decrease in glass transition temperature and change in some of the rheological and mechanical properties such as viscosity and elasticity (Dopfer et al. 2013). This behaviour may result in visco-elastic deformation of particulates and hence improved adhesion by increasing contact area between the particles and hence decreasing distance between the particle surfaces which leads to an increase in Van der Waals forces (Dopfer et al. 2013).

The F_{vdw} can be calculated for two spheres (ideally smooth and rigid spheres) of diameter d_1 (m) and d_2 (m) separated from each other by distance x (m) (Adhikari et al. 2001), as:

$$F_{vdW} = \frac{E_p d_1 d_2}{16\pi \left(d_1 d_2\right) x^2} \tag{3.6}$$

Ep, the Van der Waals' interaction energy ($10^{-19} - 10^{-18}$ J). In the case of particles are in close contact with each other, Van der Waals' force (N) is becoming stronger. Eq. (3.6) can be applied to both particle-particle and particle-plane interfaces (Schubert 1987).

3.4.3 Capillary Forces and Liquid Bridges

This kind of adhesion forces are generated by low viscosity liquid bridges between particle-surface systems. It has been reported that capillary forces are becoming dominant over electrostatic and vdW forces when there is a low viscosity liquid layer in between a particle (Fig. 3.3) and a surface of a substrate (Dopfer et al. 2013; Wang et al. 2017). The capillary forces between two particles could be calculated using different approaches. Rabinovich et al. (2005) used a total energy approach to determine capillary forces. Van der Waals forces exhibit a stronger decrease when compared to capillary forces in the case of increasing separation distance between particulate systems. A number of publications cover adhesive forces generated between particles having liquid bridges in between (Dopfer et al. 2013; Payam and Fathipour 2011; Megias-Alguacil and Gauckler 2009; Simons 2007).

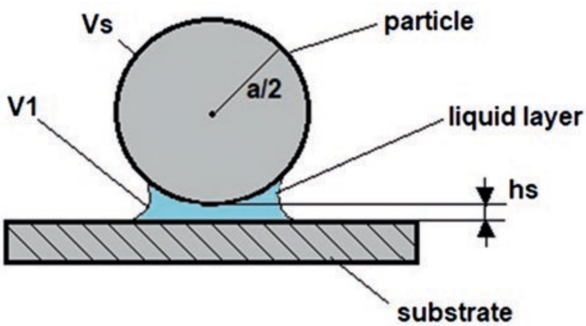

Fig. 3.3 Adhesion of a particle due to capillary forces. (V1/Vs is liquid to solid volume ratio, a is particle diameter, hs is separation distance)

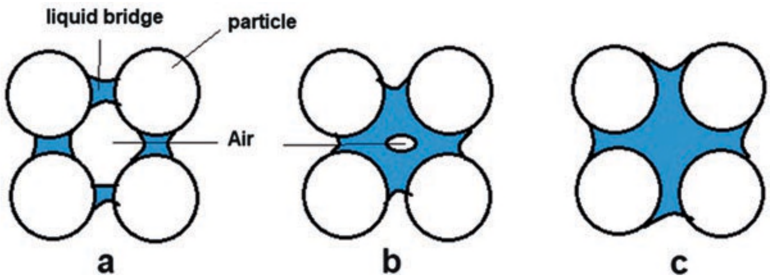

Fig. 3.4 Schematic illustration of immobile liquid bridges. a-pendular state, b-funicular state, c-capillary state [adapted from Peleg (1977)]

Liquid bridges between particle-surface or particle-particle improve adhesion and cohesion phenomena. These liquid bridges can be classified as mobile and immobile and immobile ones can be divided into three groups: pendular, funicular and capillary state (Fig. 3.4) (Adhikari et al. 2001).

Liquid is absorbed at the surface of the granules as well as it penetrate into the supra-molecular and capillary structure of the particles. This liquid transfer by the time affects the adhesion caused by capillary forces. In general, when the relative humidity of the storage unit where powder material kept is above 70%, capillary forces predominate (Halim and Barringer 2007).

3.4.4 Mechanical Inter-Locking

Interlocking or folding action may occur between fibrous, bulky, and flaky particles having irregular surface characteristics and this may result in "form-closed" bonds (Pietsch 2003). This mechanical bonding (mechanical interlocking/matting/meshing between the particles) occurs especially when the temperature of the material rise to certain degrees to cause molecular flow into each other (Griffith 1991).

3.5 Methods to Measure Particle Adhesion

Various test methods and test equipments have been developed to measure adhesive forces between the interface of paticle-particle and particle-surface (Table 3.1). Some examples are given as Atomic Force Microscopy (AFM), centrifugal detachment, electric field detachment, aerodynamic detachment, drop test, impact tester and vibration method (Zafar et al. 2014; Karasu and Ermis 2019; Ermis et al. 2011). Most of the methods developed for measuring particle adhesion are either time-consuming or experimentally demanding or not practically applicable. Since most

Table 3.1 Adhesion measurements methods [adapted from Ermis et al. 2011]

Method	Operation	Advantages	Disadvantages
Centrifugation	• Tangential detachment • Image analysis/ weighing before and after testing	• Accurate and repeatable • Simple and well established • Good statistics	• Similar size of particles need to be used • Cohesive powders might be problematic • Time consuming
Aerodynamic detachment	• Detachment at angled positions by air jet • Image analysis/ weighing before and after testing	• Flexible on substrate size • Good statistics	• Particle-particle collisions and particle layers on the surface need to be considered • Velocity of air is high
Hydrodynamic detachment	• Detachment caused by liquid stream • Image analysis/ weighing before and after testing	• Flexible on substrate shape • Good statistics	• For only insoluable particles
Impact separation	• Detachment by impact on particles surface with adhered on opposite side • Image analysis/ weighing before and after testing	• Test method is not complicated, easy to conduct • Relatively low capital cost • Good statistics	• Fine particles need high g forces • Existence of a liquid layer cause capillary force and hence more impact force required • May damage surface-particle systems at high impact forces
Vibration	• Detachment by acoustic transducer • Image analysis/ weighing before and after testing	• May be used with liquids • Good statistics	• May damage surface-particle systems at high vibration forces • Plastic deformation may occur
Electrostatic detachment	• Voltage is applied between electrodes • Image analysis/ weighing before and after testing	• Relatively fast method • Good statistics	• For only charged particles
Atomic force microscope (AFM)	• Optical beam deflection is proportional to deflection of cantilever • Piezoelectric sensor measures the force needed to detach the particle	• Precision and control is high • Same particle can be tested at different conditions • Different tips distance • Short contact time • Measures attractive as well as removal force	• Long time needed for sample preparation • Cohesive powders may cause difficulties • Capital cost is high • Enough number of tests need to be conducted for statistics • Poor statistics

of the techniques are not usable for routine applications, researchers have been focusing on a simple alternative method.

The techniques studied so far had different mechanisms and approaches to measure particle adhesion. Therefore they produce varios measure of adhesion. Some examples to the approaches are surface contact measurement and particle deposition and detachment (Hu et al. 2010). Surface topography, particle physical properties (shape, size, surface structure, particle density etc.) and contact geometry affect the measured adhesion force (Packham 2003). Temperature and moisture are extrinsic parameters affecting the magnitude of adhesion force (LaMarche et al. 2010).

Some of the methods such as Atomic Force Microscopy (AFM) may be costly and focus on single particle only. However some applications involve bulk powder treatment and a need for rapid and reliable test method was arised. For this reason the drop test method (Zafar et al. 2014) and impact adhesion tester (Ermis et al. 2011) have been developed and studied to be able to determine adhesion of powders attached to the surfaces in bulk to mimic the industrial applications such as flavor coating. In these test methods particles which adhered to the surface of a substrate are attached on a sample holder and they are subjected to a tensile force/impact force by impacting the stub against a stopper by dropping it from a set height. Vibration method was studied by (Vahdat et al. 2013) and Hopkinson bar technique was applied by (Wanka et al. 2013). A review of detachment methods was presented by (Petean and Aguiar 2015).

3.5.1 Colloidal Probe Technique/Atomic Force Microscopy (AFM)

The AFM technique have been used by different researchers to characterize particle adhesion (Kappl and Butt 2002; Beach et al. 2002; Duri et al. 2013). However, it only measures single particle adhesion and too many tests need to be conducted due to irregularities of the particles to have reliable data, a limiting factor for representative number of particles that can be investigated (Wanka et al. 2013). Each single particle has to be attached manually to the end of a microcantilever making it not suitable for measuring bulk powder adhesion. In addition, the equipment is expensive and the measurement is time-consuming and for obtaining reliable data, several measurements need to be conducted for irregular particles because of variations of contact geometries and local surface properties.

3.5.2 Centrifuge Method

The adhesion between particle and surface of a substrate can be determined by measuring the force generated by angular speed of rotation of a particle adhered to the surface of a substrate placed in a rotor of a centrifuge with a defined particle mass at a known distance to the rotation centre (Ermis et al. 2011; Salazar-Banda et al. 2007; Karasu and Ermis 2019; Knoll et al. 2015). Varying rotational speeds can be applied on the substrate where particles are attached to determine particle detachment from the surface. In this method, the necessary force to detach the particles varies proportionally to particle size, particle shape and surface characteristics. The adhesion force, generated in the detachment direction, acting on a single particle can be calculated by Eq. 3.7 (Salazar-Banda et al. 2007).

$$F_{cen} = m\omega d^2 dc \tag{3.7}$$

where m is the mass of the particle, wd is the angular speed necessary for detachment and dc is the distance between the sample and the rotor centre (rotational axis).

By using centrifuge method, adhesion forces of a large number of particles can be measured simultaneously even though the time needed for each test might be long due to spin up/down action for each acceleration.

3.5.3 Electrostatic/Electric Field Detachment

Another method studied to characterise particle adhesion is electrostatic detachment (Takeuchi 2006). In this method, electric field is used to remove particles from the surface. This method can be used only for electrically conductive particles which limits its use.

3.5.4 Aerodynamic/Hydrodynamic Detachment

The earodynamic method was employed to measure particle adhesion by using a gas or air stream across the surface (Enggalhardjo and Narsimhan 2005; Shukla and Henthorn 2009). It was reported that in this method, particle–particle collisions may occur and the drag force may be influenced by the close proximity of the particles and this may lead to breakage of the particles. This technique uses controlled (or estimated) shear stress conditions (i.e. fluid flow over the surface) and monitor the response of the particle (Burdick et al. 2005). This technique is limited to insoluable particles and surfaces when liquid is used.

3.5.5 Inertial Detachment

Wanka et al. (2013) developed a method to determine particle adhesion of fine powders on a surface based on the acceleration generated by the free end of a Hopkinson bar (a long slender titanium bar) which a schock pulse is excited on one end by a bullet from an air gun. In this technique, high acceleration (around 500,000 g) of the bar retract the surface and particle detachment take place due to their inertia. The bar is excited mechanically to provide the acceleration necessary to detach the particles from the surface. This happens when the adhesion force of the particle exceeds by the inertial force provided by the bar (Wanka et al. 2013).

$$F_{ad} = F_{detach} = \rho \frac{4}{3} \pi R^3 a \tag{3.8}$$

where ρ is the particle density, R the particle radius, and a the acceleration of the surface.

3.5.6 *Impact/Drop Detachment*

A bench size impact tester was designed by Ermis et al. (2011) to determine the magnitude of adhesion forces between particles and surface. The tester had a vertically moving platen which was reported to generate upto around 100 g-force depending on the drop height. Similarly, a drop test method was designed and used by Zafar et al. (2014). The principle of this test include particle detachment by the momentum of the particles caused by the sudden deceleration of the substrate attached to an aluminium stub inside a glass tube. For both techniques, the force required to remove a given fraction of adhering particles from the surface of the substrate is calculated by Newton's second law of motion, using a calculated particle mass (based on size, density and acceleration of the particle). Detached particles can be investigated either using a laboratory balance based on weigh loss or by microscopy and image analysis.

For a critical particle size, the detachment take place above the threshold force required to detach the particle and they remain on the surface below the threshold force required to detach the particle. The force needed to detach a particle can be determined using Newton's second law of motion. The variables need to be estimated are particle size, acceleration and particle density. (Zafar et al. 2014) have tested various material such as silanised glass beads, Avicel, α-lactose monohydrate and starch using a drop test apparatus based on microscopic observations of number of particles. The measurement approach is similar to that proposed by (Ermis et al. 2011). They designed and introduced impact adhesion tester (IAT) to be used in food powder adhesion on food surfaces. On impact, a tensile force is generated on the particles, causing detachment action due to the balance between the tensile force and the adhesion strength. The amount of particles detached was calculated by measuring the weight of the coated substrate before and after impact. The principle of both techniques rely on the particle detachment by the momentum of the particles on the substrate while applying varying deceleration. The detachment force can be determined using Newton's second law of motion. Particle mass, based on its volume and density as well as particle deceleration need to be determined to calculate the force needed tp detach a particle.

3.5.7 Vibration Technique

Additionally, it was reported that vibration caused rolling of particles on the surface before detaching and this behaviour reduced the adhesive force between the particles and surface (Kobayakawa et al. 2015).

3.5.8 Resonance Frequency/Vibration

In resonance frequency method, a rocking motion is generated by air acoustic transducer or ultrasonic transducer connected to flat surface (Vahdat et al. 2013). Resonance frequency (excitation by a short acoustic pulse) is used in this method to bring about the rocking motion on the surface where particle has been adhered.

The vibration technique as an alternative method has been developed and studied by (Kobayakawa et al. 2015). A piezoelectric vibrators are employed in this method to generate sinusoidally alternating stress to detach particles from the surface of the substrate. The amplitude of vibration can be controlled and detached particles are analyzed using a high-speed microscope camera. In this method the vibration may flatten the asperities and cause an intensification of the adhesion force (Ripperger and Hein 2008).

Wanka et al. (2013) used Hopkinson bar to determine particle adhesion. The detachment of particles are monitored by an optical microscope while subjecting fine particles to around 500,000 g acceleration. These kind of techniques are limited to test fine particles' adhesion ranging from 3 to 20 μm. One disadvantage of vibrational techniques might be a possible plastic deformation and thus damage to surface and particles at high vibration force.

3.5.9 Mathematical Models

For estimation of the adhesion strength between the particles and the surface, different mathematical models have been studied to describe the contact mechanics of particles. The most widely used methods are the theories of Johnson–Kendall–Robert (JKR) (Johnson et al. 1971) and Derjaguin–Muller–Toporov (DMT) (Derjaguin et al. 1975). The work of adhesion (WA) is defined as the amount of reversible work required to separate a unit area of the surfaces from contact to infinity (Derjaguin et al. 1975).

JKR theory is based on the Hertz analysis, with the addition of adhesion energy modifying the contact area and requiring a pull-off force, which is related to the surface energy of the contact, to detach the adhered particles. This theory consider all short range contact forces exist within the contact area evenly distributed. This approach is more appropriate for soft materials with significant adhesive forces (Johnson et al. 1971).

DMT theory considers molecular attraction between particles acting outside the contact area (estimation of non-contact forces). The DMT model describes weak attraction between stiff materials (Derjaguin et al. 1975).

Both models assume elastically deformable solids in contact with either sphere–sphere or sphere–plane geometries. These models predict a pull-off force necessary to separate the particle from another particle or from a surface.

$$F_{ad} = 2\pi R W_A \left(\mathrm{DMT}\right) \tag{3.9}$$

$$F_{ad} = \frac{3}{2}\pi R W_A \left(\mathrm{JKR}\right) \tag{3.10}$$

where R is the radius of the spherical particle in contact with a plane surface or with another particle. Since work is required to separate the solid surfaces in contact, molecular adhesion can be depicted in terms of energy (Petean and Aguiar 2015).

Based on to the DMT and JKR models, mechanical properties and the geometry of the particle and substrate defines the particle–substrate adhesion. However, the particle– substrate adhesion is also affected by some other factors (i.e. the surface roughnesses of the particle and substrate; the electrostatic charge and the relative humidity of the environment) (Liu et al. 2011). Comprehensive reviews on the fundamentals of contact mechanics are given elsewhere.

3.6 Conclusion

The theoretical and experimental studies have been done about adhesion mechanisms of particulate systems up to date suggested that the material properties such as hydrophobicity, hygroscopicity, mechanical/rheological properties and particle properties (size, shape and surface properties) need to be better understood to describe and better understand complex adhesion and cohesion behaviour of food powders. Most of the research work has been done in the recent years on particle adhesion has been focused on single particle/cell adhesion. However, there is still research work to be done about adhesion of food particles in bulk onto food surfaces at full production scale operations (i.e. snack food manufacturing).

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