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Original Research Paper

Adhesion force approximation at varying consolidation stresses for fine powder under humid conditions

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ABSTRACT

Interparticle adhesion forces in fine powders are greatly influenced by varying relative humidity (RH) conditions. The present study estimated the interparticle adhesion forces developed in corn starch powder under humid conditions at varying applied consolidation stresses using tensile strength determination approach. Shear test was used to determine tensile strength of powder at 1–9 kPa consolidation pressures and extrapolated values of tensile strength at zero stress were used for force estimation in non-consolidated powders. A strong dependence of interparticle adhesion force on consolidation and RH conditions was observed, mainly due to alteration in the number of adhesive contacts and contact area. The results indicated that, at low consolidation and high RH, capillary force is the prevailing force contributing to the total interparticle adhesion in contrast to higher consolidation conditions where load induced contact force plays a dominant role. Furthermore, for nonconsolidated samples, the adhesion forces registered a steep jump above 60% RH which was primarily attributed to dominance of the liquid bridge forces. Also, forces determined from tensile strength approach and those predicted theoretically, as a summation of individual forces, yielded a similar trend. Overall, a simple and effective approach for interparticle force estimation of consolidated as well as loosely packed powders under varying humidity conditions is presented here.

1. Introduction

Particle adhesion phenomenon is dependent on different interparticle forces existing in the system. Among these forces, the van der Waals interactions are ubiquitous for all particles in all the conditions. In contrast, the influence of other forces like capillary, electrostatic and friction are conditional. It is well known that at higher relative humidity (RH), capillary forces may contribute largely to the interparticle adhesion forces [1–3]. However, the actual impact of humidity on adhesion may depend on number of factors like particle size, shape, roughness, material properties like elasticity modulus, hardness along with packing or consolidation state of powders [4–7].

The compressive stresses in powder bed influences powder behavior to a great extent [8], especially in cases when the powder is stored in silos, hoppers, etc. These compressive forces developed during storage, handling or processing are important consideration while determining particle adhesion. Depending upon the industrial processes involved, these compressive stresses exerted could vary from very high (during compaction) to lower values (during mixing, separation, dispersion, fluidization). Further, introduction of humidity could make the situation much more complex. As such, the typical effect of humidity on powder bulk behavior is familiar to powder flow community [9–12]. However, a combined effect of humidity and applied consolidation on powder behavior is not studied well. In such cases, the estimation of total adhesion forces in powders exposed to different RH conditions at varying compressive stresses can provide a much better understanding of powder flow for different applications.

Due to the complexities involved in direct determination of interparticle forces and varied nature of factors affecting it, the scientific literature is in real need of a simple, easy and suitable approach to calculate or predict these forces. Rumpf [13] proposed a model for estimating the total adhesion forces among particles from the bulk stresses developed in powder bed under consolidated state and was applied even for wet materials [14]. However, in complex systems which considers the influence of humidity for powders under compressive stresses; the total adhesion forces (F_T) can be described as the summation of mainly van der Waals forces (F_{vdW}), compaction force (F_{com}) and capillary forces (F_{cap}). According

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to Rumpf (1956) and Molerus (1975), the total interparticle adhesion forces (F_T) in a consolidated powder bed can be approximated from its tensile strength (σ_t) and bed porosity (ε). The generalized Rumpf expression, assuming the particles are spherical in nature and isostatic bed compression, is given below,

$$\sigma_t = \frac{(1-\varepsilon)}{\varepsilon}\frac{F_T}{d^2} \quad (1)$$

where F_T include van der Waals, capillary and compressive forces and d is the particle diameter in microns.

This equation directly correlates the total interparticle forces to the tensile strength of powder bed. In short, this model provides the adhesion force estimation from bulk particle detachment approach. This is practically more relevant approach than the individual particle detachment method performed using AFM, since assemblage of particles exists together to constitute a powder mass. The tensile strength, which is defined as the minimum force required to separate bulk structure in powder bed, can be considered as the sum of the adhesive forces at large number of particle contacts. Thus, it is an important indicator of adhesive interaction between the powder particles [15]. There are different methods and approaches used for determining tensile strength of powders depending on the type of testers available [16–19]. Although direct measurement of tensile strength using specific tensile strength testers is possible, shear testers can also be used to calculate the tensile strength of powders at different consolidation stresses. The shear cell data provides an indirect measurement of tensile strength of powder bed from the derived Mohr-Coulomb parameters [20–22].

As such, measuring the tensile strength of a powder system at very low consolidation stresses has always been a challenge. Since, measuring the cohesive behavior of particles at extremely low consolidation stresses is difficult, majority of the previous studies have subsequently determined adhesion forces under applied consolidation loads [8,22]. However, for the systems existing in loose state or stored under the consolidation of its own weight, the interparticle adhesion forces may vary considerably from those determined under applied consolidation. Valverde and coworkers have previously reported the methodology to determine the tensile strength of powders under low consolidation stresses [8,23–25]. They used gas fluidization technique for determining the tensile strength of powder bed under low consolidation state. However, for cohesive powders (Geldart group C), supplementary measures such as addition of flow additives or using vibration aid during fluidization are generally employed. These additional arrangements could change the interparticle contact geometry and are bound to affect the actual force measurements significantly. Another problem of this approach is that, while studying powders under different RH conditions, it becomes very difficult to discern the actual contribution from capillary forces and that from the applied consolidation pressure to the total adhesion force. Overall, it can be said that in case of cohesive powders under the influence of RH existing in loosely packed or under low compressive stresses, the determination of total interparticle adhesion force is a difficult task to achieve and is clearly lacking in the available literature.

The objective of this study is to estimate the interparticle adhesion forces developed in a complex powder system involving fine hygroscopic powders at varying humidity and under relatively low consolidation (<10 kPa) conditions. The tensile strength of a fine hygroscopic corn starch powder conditioned at different humidity levels was determined using shear test experiments performed in powder rheometer at different consolidation stresses and the average interparticle adhesion force was estimated using the Rumpf model. Furthermore, this paper also attempts to determine the interparticle adhesion forces in non-consolidated powder system using extrapolated tensile strength approach. The results obtained were then compared with summation of individual forces obtained using different theoretical models available for van der Waals, compressive and capillary force calculation.

2. Experimental

2.1. Powder sample conditioning

Powder samples were placed and uniformly spread to a thin layer in a stainless steel tray. The samples were kept in a humidity chamber (HMG India, India) to equilibrate at preset relative humidity and temperature conditions. All the samples were exposed to five different humidity conditions of 30%, 45%, 60%, 75% and 90% RH in the increasing order for adsorption studies, with the temperature kept constant at 25 ± 2 °C. Fig. 1 represents the schematic diagram describing the sample preparation and bulk property testing methods.

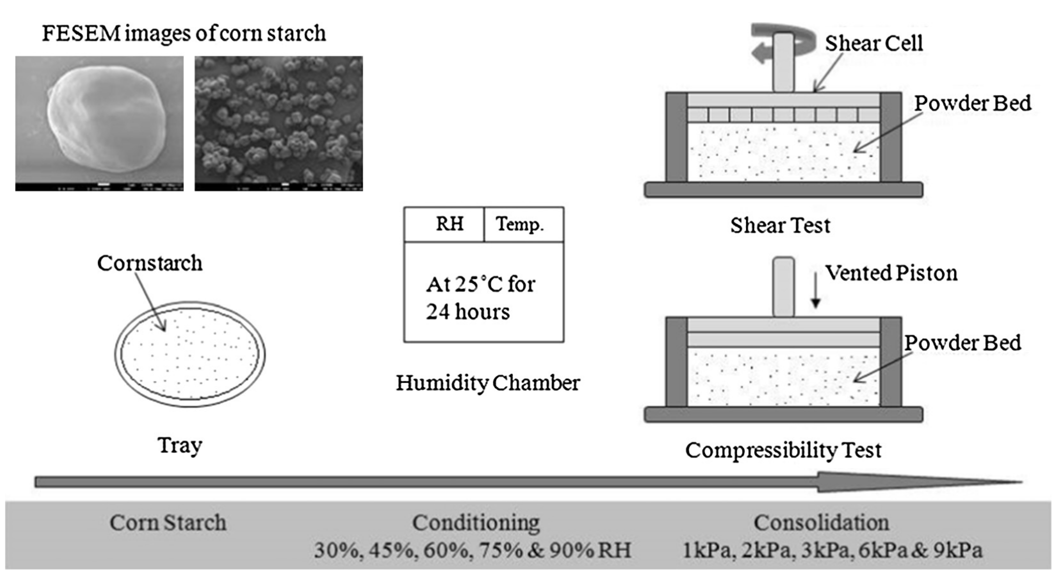

Fig. 1. Schematic showing the sample preparation and bulk testing methods used for corn starch powder along with the FESEM images of particles.