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Physical study on the vibrated packing densification of mono-sized cylindrical particles

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ABSTRACT

Systematic physical experiments examining the packing densification of mono-sized cylindrical particles subject to 3D mechanical vibration were carried out. The influence of vibration conditions such as vibration time, frequency, amplitude, vibration strength, container size, and the aspect ratio and sphericity of the particle on the packing density were analyzed and discussed. For each initial packing density with a certain aspect ratio, operating parameters were optimized to achieve much denser packing. The results indicate that the packing density initially increases with vibration time and then remains constant. The effects of vibration frequency and amplitude on the packing densification have similar trends, i.e. the packing density first increases with the vibration frequency or amplitude to a high value and then decreases; too large or small frequency or amplitude does not enhance densification. Increasing the container size can reduce container wall effects and help achieve a high packing density. Varying the particle aspect ratio and sphericity can lead to different dense random packing structures. Overall, based on results of the examined systems, the highest random packing density obtained in an infinite sized container can reach 0.73, which agrees well with corresponding numerical and analytical results in the literature.

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Introduction

Particle packing is of wide concern in both scientific research and engineering applications (Bideau & Hansen, 1993; German, 1989). One important branch of research that has increasingly attracted much investigation, concerns the packing densification of particles because different particle packing densities can lead to different packing structures and resultant material properties. Therefore, a large amount of work was carried out in this aspect over the past few decades. Because of the simplification of particle shape, the packing of spherical particles was first studied and understood. For example, for the packing of mono-sized spheres, three well known states can be reproduced according to the packing density ρ (an alternative representation is the packing porosity ε with $\varepsilon = 1 - \rho$): random loose packing with $\rho \leq 0.60$ (Bernal, 1959; Bernal & Mason, 1960; Scott, 1960), random close packing with $\rho \approx 0.64$ (An, Li, Yang, Zou, & Yu, 2009; An, Yang, Dong, Zou, & Yu, 2005; Ayer & Soppet, 1965; Bernal & Mason, 1960; Berryman, 1983; Knight, Fandrich, Lau, Jaeger, & Nagel, 1995; Nolan & Kavanagh, 1992; Scott,

1960; Scott & Kilgour, 1969; Stachurski, 2003; Torquato, 2000; Woodcock, 1976; Wu, An, & Huang, 2014), and ordered packing with the maximum $\rho \approx 0.74$ (An & Huang, 2013; An, Yang, Dong, & Yu, 2011; Blair, Mueggenburg, Marshall, Jaeger, & Nagel, 2001; Li, An, Yang, Zou, & Yu, 2011; Owe Berg, McDonald, & Trainor, 1970; Roche, 1971; Spannuth, Mueggenburg, Jaeger, & Nagel, 2004; Tian, Dong, & Yu, 2014; Van Blaaderen, Ruel, & Wiltzius, 1997; Yu, An, Zou, Yang, & Kendall, 2006). These results are meaningful because they can be used as effective models to study the structures of simple liquids, amorphous metals and alloys, and crystalline granular materials (Rintoul & Torquato, 1996). To overcome the bottle-neck in studying the packing densities of equal spheres, many numerical and physical experiments on the packing densification of binary (An, Li, & Qian, in press; Clarke & Wiley, 1987; Zheng, Carlson, & Reed, 1995; Zou, Feng, & Yu, 2001), ternary (Leitzelement, Lo, & Dodds, 1985; Standish & Yu, 1987; Wong & Kwan, 2014), multimodal and continuous-sized (Liu & Ha, 2002; Yu & Standish, 1987; Zou, Gan, & Yu, 2011) sphere mixtures were conducted to realize higher packing densities.

In addition to the numerous studies of dense packing of spheres, less work has focused on the packing densification of non-spherical particles, in large part because of the complexity of particle shape effects. However, as already known, most particles people

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encounter within both daily life and industrial production have non-spherical shapes. For example, cylindrical particles with fiber-like shapes have been widely applied in chemical engineering fields (Ahmadi Motlagh & Hashemabadi, 2008; Bey & Eigenberger, 1997). Generally speaking, the packing behavior of cylindrical particles is fairly different from spheres because the former exhibit orientational anisotropy and the geometry contains a variety of surface elements (Zhang, Thompson, Reed, & Beenken, 2006), which makes it inappropriate to study packing densification of cylindrical particles by simply using sphere packing models. For these cases, many numerical and analytical models (Abreu, Tavares, & Castier, 2003; Blaak, Frenkel, & Mulder, 1999; Blouwolf & Fraden, 2006; Caulkin, Ahmad, Fairweather, Jia, & Williams, 2009; Coelho, Thovet, & Adler, 1997; Nandakumar, Shu, & Chuang, 1999; Nolan & Kavanagh, 1995; Zhao et al., 2011) have been proposed that aim to describe the packing densification of cylindrical particles. In comparison, physical experimental studies on the dense packing of cylinders are limited. Early experiments were conducted by Milewski (1973) to study cylindrical particle packing using wooden rods (aspect ratios from 4 to 72) and milled glass fibers (aspect ratios from 6 to 60). He concluded that the solid fraction of random packing decreases as the cylinder aspect ratio increases. Dixon (1988) measured the void fraction of fixed beds of equilateral cylindrical particles. The columns were packed by slow pouring of the packing material manually without tamping, and a random loose packing fraction of 0.64 was obtained. Foumeny and Roshani (1991) later extended this work by considering the packing of cylinders with aspect ratios of 0.5–3. Particles were simply poured into a container and gently vibrated in order to get a much denser packing. They obtained a minimum porosity of 0.293 within the container. Zou and Yu (1996a, 1996b) carried out a series of physical experiments on the random packing of cylindrical particles with aspect ratios up to 100, and the measured random packing densities were in the range of 0.6–0.71. Zhang et al. (2006) used X-ray microtomography to obtain 3D images of equilateral cylinders (1.8 mm in diameter) in a 23-mm-diameter cylindrical container over a range of packing porosities; random packing densities between 0.594 and 0.715 were obtained. Benyahia (1996) investigated the packing of non-equilateral cylinders with aspect ratios 0.25, 0.5, 2, and 3, and compared these with the results of packing spheres and equilateral cylinders of similar dimensions. He reported that the mean voidage of beds packed randomly with equilateral cylinders is found to be consistently lower than that of beds of non-equilateral cylinders and spheres. Sharma, Mantle, Gladden, and Winterbottom (2001) used a water substitution method and magnetic resonance imaging experiments on packing of equilateral cylinders. By changing the container diameter and tapping, typical bed voidage values of 0.28–0.31 were obtained. By applying 1D vibration to the packing of granular cylinders, Blouwolf and Fraden (2006) measured the contact number distribution between randomly packed right cylinders. In their work, the experimentally obtained maximum random packing density is about 0.70. The above analyses indicate that independent of numerical/analytical models or physical experiments, there remains no agreement regarding the densest random packing for different cylindrical particles. With the maximal packing densities still in controversy, their densification behavior when subjected to external energy, for example 3D periodic mechanical vibrations, as well as the influences of various factors on packing densification and the optimization of operating parameters for each case need to be comprehensively studied and identified.

The objective of the current work is to carry out systematic studies on the random packing densification of different cylindrical particles subjected to 3D mechanical vibration. The research focuses on realizing the densest random packing structures of different cylinders and understanding the influence of various parameters such as the vibration time t , frequency ω , vibration

Table 1
Particle parameters used in the physical experiments.

l (mm)	d (mm)	l/d	Material density (g/cm^3)	φ
10.04	3.6	2.78	0.677	0.7924
5	10	0.5	0.677	0.8256
10	10	1	0.677	0.8737
50	10	5	0.677	0.6971

amplitude A , vibration strength S , container size D (wall effects), and particle geometry parameters (the aspect ratio l/d and sphericity φ) on the packing densification. Here, the sphericity is defined as the ratio of the surface area of a sphere having the same volume as the particle to the surface area of the particle; l and d represent the length and diameter of the cylinder, respectively. During the physical experiments, we mainly concentrate on the following points: (a) to realize the attainable highest random packing densities of cylindrical particles; (b) to identify the effects of vibration conditions and cylinder geometry parameters on the packing densification; and (c) to validate the proposed analytical model.

Experimental procedure

The physical experiments were conducted using our self-designed vibration device which can produce vibrations in three orthogonal directions with independently variable amplitudes and frequencies. All the vibration amplitudes and frequencies are accurately controllable and adjustable, where the vibration amplitudes are controlled by the eccentricity of each cam linking with the shaft and the vibration frequencies are controlled by the rotational speed of each motor governed by the converter. The vibration in each direction follows a sinusoidal waveform with the governing equation $Di(t) = A(\sin \omega t + \phi_0)$, where Di represents the displacement, and t and ϕ_0 are the vibration time and initial phase angle, respectively. In this work, the same A and ω were employed in three vibration directions and all initial phase angles are set to be zero. This vibration device has been successfully used in our previous experiments on the packing densification of spheres (An, He, Feng, & Qian, 2015; An & Li, 2013; An et al., 2009; Tian et al., 2014) and cubes/spheres mixtures (An et al., 2015). Table 1 lists corresponding shape parameters of the particles used in this study. Particles with different aspect ratios or sphericity were chosen to study the role of particle shape in vibrated packing densification.

Before vibration, the containers made of polymethyl methacrylate materials were cleaned using distilled water and dried in an oven at 60 °C in preparation for the experiments. Subsequently, a certain quantity of cylinders (wooden rods) was weighed and then gently poured into the container (total feeding) which was fixed on the vibration desk to form the initial packing. The initial packing density was calculated by averaging the packing heights measured at different positions. The packing was then vibrated at a given condition for a period of time and stopped and the packing density was re-measured. The vibration amplitude A (the adopted amplitudes, determined by cams with different eccentricities, are $A = 0.15, 0.35, 0.5, 0.8,$ and 1.0 mm), frequency ω (ranging from 30 to 120 rad/s), particle aspect ratio l/d , and sphericity φ were varied to study their effects on the packing structure. Four different sized containers ($D = 109.90, 140.38, 185.77,$ and 229.70 mm in inner diameter) were used to identify container size effects. All experiments were repeated three times and the average value for each set of fixed parameters was taken so as to minimize error. Fig. 1 displays a flowchart of our physical experiments. As indicated, various parameters were allocated through orthogonal experimental design, and each parameter varies over a certain range. In order to identify the effects of each parameter, other parameters are fixed and only the value of the studied parameter changes with each

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