Study of the effect of vibrocompaction modes, shape of particles and their size distribution on packing density

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Abstract. The results have been described of experimental studies of the influence of vibrocompaction modes, shape of particles and their size distribution on the relative package density. The glass spheres with diameters distributed from 0.4 to 0.9 mm and from 0.63 to 0.8 mm, containing a fraction of nonspherical particle inclusions of about 30 % have been taken as the research object. Also in the experiments the powder was used of electrocorundum with particle size of 0.63-0.8 mm. This choice was aimed at bringing the particles characteristics to those of a real granular material and no separation of particles into spherical and non-spherical was planned. The experiments on vibrating packing have been performed with the help of dynamic “Revolution” powders rheometer. The modes of compaction vibration varied over a wide range of frequencies and amplitudes: from 5 to 475 Hz and from 106 to 1062 µm, respectively. The vibration frequency has shown to exert a greater effect on relative density as compared to that of the amplitude. The dependence of relative density on vibration frequency exhibits several local maxima for all vibration amplitudes. The maximum relative packing density of 0.64 ... 0.65 is achieved at a combination of high amplitude (850, 1062 µm) and high frequency (300 ... 350 Hz). Effect of granulometric composition on relative packing spheres density is less pronounced than that of the vibration frequency and approximately equals to than of the amplitude. Increasing the deviations of the particles size is accompanied by increasing frequencies leading to maximum packing density. The particles shape affects the level of packing density, thereby remaining the same character of dependence of relative density on vibration frequency for both spherical and non-spherical particles of similar particle size distribution.

1. Introduction

The study of structure and density of particle packages obtained using vibration is a relevant task for various fields of applied science and materials technology. Application of vibrocompaction of free-flowing materials to increase the density of their packaging is of great importance in the technology of ceramics and powder composite materials, pharmaceutical, cosmetic and food industries. There are some literature data describing the studies of particle vibrocompaction, mainly carried out on model particles - glass and metal spheres [1-3]. The research has been carried out dealing with the compaction of spherical particles in cylindrical containers on vibratory tables, as well as with virtual experiments on numerical simulation of vibrocompaction of spherical and cubic particles in containers using the method of discrete elements [1-6]. However, these studies considered practically the same ranges of frequencies and amplitudes of vibration. Thereby the regimes have been varied in relatively
narrow ranges: frequencies from 2 to 70 Hz, amplitudes from 0.1 diameter to 0.8 diameter of the spherical particles used. Moreover, diameter deviations of model spherical particles in [1-3] did not exceed 1%.

According to the general conclusions of [1-5] the relative packing density initially increases with increasing vibration amplitude or frequency to the maximum value and then decreases; the greatest relative packing density is achieved by combination of low frequency and large oscillation amplitude, or high frequency and low amplitude.

The aim of this work is to reveal the regularities relating the vibrocompaction regimes over a wide range of variation, shape of particles and their size distribution with the relative density of their packaging.

The experiments have been performed over a wide range of frequencies and amplitudes: from 5 to 475 Hz and from 106 to 1062 µm, respectively. For better approximation of the real free-flowing material by the model system of spheres the glass spheres have been used with a significant size deviation from 0.4 to 0.9 mm containing about 30% fraction of inclusions of non-spherical particles. As mentioned above, the conventional industrial glass spheres were taken as the material for experiments and no separation of particles was planned. In further studies, the influence of the mass fraction of non-spherical particles on the packing density will be analyzed. In addition, the experiments have been carried out with industrial electrocorundum powder, not having spherical particles, to compare the results of vibrocompaction of model spheres with the real free-flowing material.

2. Experimental procedure
The vibrocompaction of particles has been carried out using dynamic powders rheometer “Revolution” of Mercury Scientific firm. The “Revolution” rheometer possesses extensive capabilities for the study of rheology of free flowing materials, their ability to consolidation and caking. Its main advantage in the study of the parameters of vibrocompaction of free-flowing materials is the possibility of varying the frequency and amplitude of vibration in wide ranges: from 1 to 1000 Hz and from 1 to 5000 microns, respectively. Application of “Revolution” rheometer in comparative studies of rheology of free-flowing materials is described in [7, 8]. The method of analysis of particles packaging, used in the “Revolution“ device, consists in shooting by digital camera free-flowing material placed in a drum with transparent walls, which is installed on the drive and support rollers. Video image is processed by special software, resulting in determination of the apparent density of given free-flowing material. The bulk density is determined at the beginning of the packaging cycle study, then the free-flowing material is subjected to vibration, caused by the return-rotational movement of the drive roller and after vibration the density is determined again. Then follows the loosening stage, effected by means of the drum rotation. Loosening is used to achieve the initial bulk density to prepare the material for the next research cycle. The cycles can be repeated many times. In this study, each experiment was repeated six cycles. Schematically, the method of studying the packaging is shown in Figure 1.

![Figure 1. Experimental procedure of investigation of powder packaging on dynamic “Revolution” rheometer: a) cycle start; b) vibrocompression; c) end of the cycle.](image-url)
The relative density of the particle packaging was determined as the ratio of the apparent density of the free-flowing material to the true density of the particle material.

The particles of different shape and true density have been experimentally studied in this work. The microscopically obtained photos of glass spheres and electrocorundum powder presented by Figure 2 show the comparison of particle shapes. In Figure 2 a), among the spherical the non-spherical particles can be seen. Their volume is about 30 %. The characteristics of the particles are presented in Table 1. Humidity of free flowing material in all experiments did not exceed 0.15 %.

![Figure 2. Photographs of the particles: a) glass spheres; b) electrocorundum powder.](image)

| Properties          | Spherical | Nonspherical |
|---------------------|-----------|--------------|
| Material            | Na-Ca-silicate glass | Electrocorundum |
| True density, g/cm³ | 2.53      | 3.96         |
| Dimensions, mm      | 0.4 ... 0.9; | 0.63 ... 0.8 |

3. Results and discussion
The results of experiments on vibrocompaction of spherical particles with a wide particle size distribution are presented in Figure 3. The graphs show the nonlinear dependence on the vibration frequency of the relative density of the sphere packing with several extremes in the entire range of the studied amplitudes. At constant amplitude, the increasing frequency is accompanied by the increase in the relative density of the package, and then by its decrease - this is consistent with the results of [1-4]. However, a further increase in frequency over 150 ... 170 Hz leads to a further increase in relative density up to higher values exceeding 0.64 ... 0.645. At the same time, at amplitudes of 850 and 1062 µm, the curves have an additional local maximum of compaction at a frequency of 300 Hz. At this frequency, and amplitude of 1062 µm, a maximum relative density of more than 0.65 is observed.

The dependences of the relative density on the vibration frequency at amplitudes of 106 and 425 microns differ significantly but they have one frequency range of 200 ... 250 Hz, where an equal relative density of 0.64 is achieved.

In the frequency range from 310 to 475 Hz the relative density decrease at all vibration amplitudes.
Thus, it can be concluded that the greatest compaction of spherical particles with a wide size distribution range can be achieved by using high frequencies and large vibration amplitudes. These results do not agree with those presented in [1-3, 5], where the greatest compaction was achieved by combining small frequencies with large amplitudes and large frequencies with small amplitudes. This can be explained as follows:
- in this work, the spheres with a significant size deviation (about 30%) were investigated, whereas in cited works experiments were carried out with monodisperse spheres having deviations in diameters less than 1 %;
- the particles used in this work have a significant portion of non-spherical particles, about 30 % by volume;
- in the present study, the modes of vibrocompaction vary in much wider ranges than in cited works.

The assessment of the effect of particle size distribution on the relative density of particle packing during vibrocompaction, has been carried out in experiments with glass spheres having a narrower particle size distribution. Initial spheres with size distribution from 0.4 to 0.9 mm were sifted on sieves to obtain the distribution of 0.63 ... 0.8 mm. The results concerning the dependence of relative density of the package on the vibration frequency at two different amplitudes are shown in Figure 4. The graphs show that spherical particles with a narrow size distribution reach a mean lower relative density at larger frequency. The local peak at a frequency of 340 Hz at an amplitude of 850 µm is the exception and requires further research. But at the same time they show a greater compaction at smaller frequency, up to 100 Hz. They have also local extremes of the relative density in much narrower frequency ranges, in comparison with the dependencies obtained for the spheres of wide particle size distribution. Thus it can be concluded that the relative packing density of spherical particles of a narrow size distribution is more stable than similar spherical particles with a wider distribution. The results in Figure 4 also agree with those of [1-4], for monodisperse spheres with a minimum deviation of their diameters.

To compare the results of vibrocompaction of model spheres with those for real free-flowing material, experiments were carried out with industrial electrocorundum powder, of a similar granulometric composition without spherical particles.
Figure 4. Dependence of relative density of sphere package with various size distribution on the vibrocompression mode.

Figure 5. Dependence of relative density of electrocorundum powder and sphere package on vibration frequency for various vibrocompression modes.

The graphs in Figure 5 show that the relative density of the packing of electrocorundum powder has the same dependence on the vibration frequency as that of the packing of glass spheres having identical ranges of particle size deviations. However, the relative density of the electrocorundum
powder packaging reaches significantly lower values, not exceeding 0.5 in comparison with 0.645 for the glass spheres. This can be explained by increased internal friction due to non-spherical shape of the particles and a large number of sharp angles. Nevertheless, it can be assumed that experiments with model spheres can predict the dependence of the relative density of the packaging with particles of non-spherical shape made of other materials with a similar particle size distribution.

4. Summary
Effect of vibration frequency on the relative density is more than that of the amplitude within the ranges studied. Vibrocompaction of spheres with a wide particle size distribution and high content of non-spherical particles (about 30% by volume), results in the maximum relative package density of 0.64 ... 0.65, this being achieved by combining large amplitude (850, 1062 µm) and high frequency (300 ... 350 Hz). The dependence of relative density of packing spheres on the vibration frequency is nonlinear with several extremes in the entire range of studied amplitudes. These results do not agree with the literature data. This discrepancy may be due to the difference in characteristics of the spheres used and experimental procedure: a wide (and narrow) distribution of spherical particles in size, the presence of non-spherical particles, as well as intervals of variation of the frequency and amplitude of the vibration impact.

The size distribution of spherical particles affects the dependence of the relative density on the vibrocompaction modes: spherical particles with a narrow size distribution reach a lower relative density at larger frequency, but at the same time exhibit greater compaction at smaller frequency. They also have local extremes of the relative density in much narrower frequency ranges, in comparison with the those obtained for the spheres with wide particle size distribution. This implies the conclusion that the relative density of spherical particles with a narrow size distribution is more stable.

The particles shape has also a considerable impact on the achieved packing density, but the relative density dependence on the vibration frequency remains similar for both glass spheres and non-spherical electrocorundum powder. Therefore the results of experiments with spherical particles can be used for preliminary assessment and prediction of the dependence of relative density powders packaging with particles of non-spherical shape, made of other materials, but having a similar particle size distribution. However this assumption requires further investigation.

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