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Abstract	The applicability and the properties of the constants of the following equation on the number of tappings and the apparent bulk density of the powder were studied. The equation is [function], where, n is the number of tappings, po, pf and pn are the apparent bulk densities of the powder at n=0, ∞ and n respectively, and k is a constant. When the particle size of the powder becomes large and the powder is easy to flow, pf and k become large. On the contrary, when the tapping strength is increased, pf becomes larger but k becomes smaller. In the packing procedure of the powder which has relatively large flocculated particles, the process separates into two steps with large and small k values. The former is the packing of the flocculated particles and the latter is the packing which is accompanied with the destruction of the flocculated particles. The equation is also true about the tapping of the powder which is loosely settled in liquids. In this case, the value of k is small, and the process is considered to be the destruction of the flocculated particles in liquids.
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On Apparent Bulk Density of Powder

(Received July 20, 1959)

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Abstract

The applicability and the properties of the constants of the following equation on the number of tappings and the apparent bulk density of the powder were studied.

The equation is

$$(\rho_f - \rho_n) = (\rho_f - \rho_o)\, e^{-kn},$$

where, n is the number of tappings, ρ_o, ρ_f and ρ_n are the apparent bulk densities of the powder at $n=0$, ∞ and n respectively, and k is a constant.

When the particle size of the powder becomes large and the powder is easy to flow, ρ_f and k become large. On the contrary, when the tapping strength is increased, ρ_f becomes larger but k becomes smaller.

In the packing procedure of the powder which has relatively large flocculated particles, the process separates into two steps with large and small k values. The former is the packing of the flocculated particles and the latter is the packing which is accompanied with the destruction of the flocculated particles.

The equation is also true about the tapping of the powder which is loosely settled in liquids. In this case, the value of k is small, and the process is considered to be the destruction of the flocculated particles in liquids.

I. Introduction

The apparatus for measuring the apparent bulk density of powder and the results, such as effects of particle size, falling height and container wall, were given previously[1].

In that paper an equation which gives the relation between the number of fallings and the apparent bulk denstiy of the powder was proposed. This paper is concerned with the development of the more detailed treatment of that equation.

II. Theoretical

When the powder in the container is tapped, the apparent bulk density of the pow-

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[1] H. Kuno, Y. Hayashi : This Proceedings, Vol. 6, No. 22, 6 (1953).

der should approach a certain final value corresponding to the tapping strength. If we assume this approach to the final apparent bulk density ρ_f to be exponential, there will be a following relation between the number of tappings or fallings n and the apparent bulk density ρ_n at n tappings, that is

$$\rho_f - \rho_n = Ae^{-kn} \tag{1}$$

Taking the initial apparent bulk density to be ρ_o, that is the apparent bulk density at $n=0$, Eq. (1) becomes

$$\rho_f - \rho_n = (\rho_f - \rho_o)e^{-kn} \tag{2}$$

or

$$\frac{\rho_f - \rho_n}{\rho_f - \rho_o} = e^{-kn} \tag{3}$$

The initial apparent bulk density ρ_o in Eq. (2) depends on the mehod of introduction of the powder in the container and on the treatment of the container before the measurement. Therefore, ρ_o can not be taken as a characteristic value of the powder. On the contrary, the final apparent bulk density ρ_f is characteristic of the powder, and shows the degree of packing of that powder at that tapping strength or falling height.

The constant k shows the rate of packing and seems to indicate the fluidity characteristic of the powder, though the value will also depend on the tapping strength.

Consequently, it can be assumed that the packing properties of the powder are expressed by the values of the two constants in Eq. (2), that is, ρ_f and k.

III. Experimental

The applicability of Eq. (2) and the values of the constants ρ_f and k were studied by the experiments on the following powders,

a) Spherical glass powder of average diameter 37.1, 21.7, 17.2, and 11.4 μ.
b) Commercial calcium carbonates.
   $CaCO_3$—P, average particle diameter 0.08 μ.
   $CaCO_3$—T, spindle shape crystal, average length 1.0 μ.
   $CaCO_3$—PC, same as $CaCO_3$—T, average length 2.5 μ.
   $CaCO_3$—CC, produced by the hydrophobic modification of $CaCO_3$—P.
c) Magnetite powder, average diameter 0.11 μ.
d) Commercial carbon black, average diameter 0.03 μ.
e) Magnesium oxide prepared by the calcination of rod-like (A) and plate-like (B) magnesium carbonates at several temperatures[2].

The apparent bulk density was measured in a graduated glass tube container, one centimeter in diameter, with the apparatus described in the previous paper[1].

[2] H. Kuno, Y. Hayashi : This Proceedings, Vol. 7, No. 24, 1 (1954).

Applicability of Eq. (2)

When we take logarithm of Eq. (2),

$$\log(\rho_f-\rho_n) = -kn + \log(\rho_f-\rho_o) \tag{4}$$

Therefore, the applicability of Eq. (2) will be proved by plotting the number of fallings n vs. $\log(\rho_f-\rho_n)$, and certifying the linearity of the plots.

As given in Figs. 1 and 2, in every case the plots give a good linear relation and we can confirm the applicability of Eq. (2).

But in several cases, such as the case of carbon black in Fig. 2, the plots separate into two straight lines of different slopes. This suggests two mechanisms of packing, which will be discussed later.

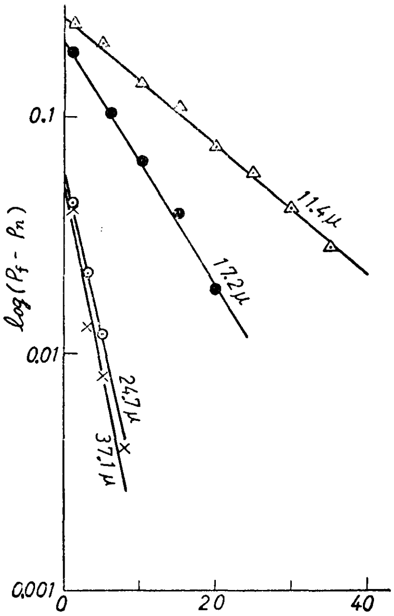

Fig. 1. $\log(\rho_f-\rho_n)$ vs. n relation of spherical glass powders. Numerals near the lines indicate average particle diameter.

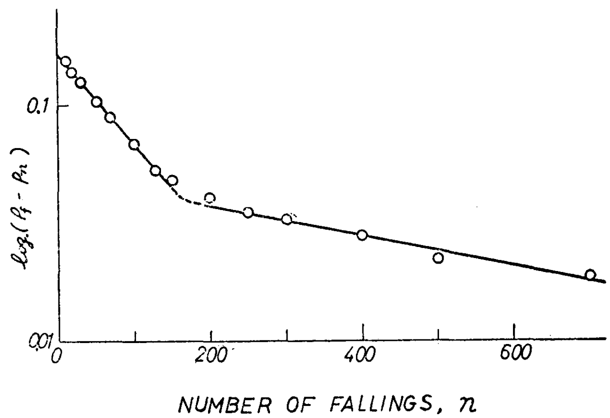

Fig. 2. $\log(\rho_f-\rho_n)$ vs. n relation of the carbon black.

Effect of Particle Size

Effects of the particle size on the constants ρ_f and k were studied on spherical glass powders. Plots of $\log(\rho_f-\rho_o)$ vs. n on these powders are given in Fig. 1, which show very fine straight lines. The values of ρ_f and k are given in Table 1.

Table 1. Packing of spherical glass powders.
Falling height: 10 mm

average particle diameter, μ	apparent sp. volume, cm³/g	apparent density, ρ_f g/cm³	$k \times 10^2$
37.1	0.707	1.415	37.6
24.7	0.717	1.394	33.0
17.2	0.733	1.365	11.3
11.4	0.747	1.339	6.3

Both ρ_f and k decrease with the decrease of the particle size. That is, the powders of small particle sizes are bulky and difficult to pack and those of large particle sizes pack quickly and dense. In other words, large particles, which we know by experience flow easily, show large values of k. This tendency can also be found in the following experiments on other powders given in Table 3.

Effect of Falling Height

When the powder in the container is strongly tapped by increasing the falling height of the container, it is easily predicted that the apparent bulk density becomes dense, and we usually think that the rate of packing will be accordingly rapid. These effects were studied on $CaCO_3$—CC, which is nonhygroscopic and easy to treat. The results are given in Table 2.

Table 2. Effects of the falling height on the packing.
Powder: $CaCO_3$ - CC

falling height mm	apparent sp. volume cm^3/g	apparent density, ρ_f cm^3/g	$k \times 10^2$
5	1.396	0.716	9.05
8	1.349	0.741	6.78
11	1.336	0.749	8.18
14	1.323	0.756	6.94
17	1.309	0.764	6.02
18	1.250	0.800	5.63

Though the final apparent bulk density becomes denser as the falling height increases, as we have predicted, but the value of k decreases with the increase of the falling height, contradicting our prediction. From the results we find that when we force to pack the powder densely in the container, the rate of packing to reach the final apparent density becomes slower.

IV. Mechanisms of Packing

The results on other powders are given in Table 3. From this table we become aware of two groups of powders, one showing only one straight line in the plots like Fig. 1, and the other showing two straight lines of different slopes in the plots like Fig. 2. Therefore, the latter has two values of k, one for each straight line, which are given in the table as k and k'. The values of k are greater than those of k'. Two straight lines mean the existence of two mechanisms of packing process, and the first step, which is expressed by k, is more rapid than the second step, which is expressed by k'.

Table 3. Apparent bulk density and values of k.
Falling height: 18 mm

powder		apparent sp. volume cm^3/g	apparent bulk density ρ_f, g/cm^3	$k \times 10^2$	$k' \times 10^2$
$CaCO_3-P$		1.640	0.609	5.17	—
$CaCO_3-CC$		1.250	0.800	5.63	—
$CaCO_3-PC$		2.191	0.456	1.61	—
$CaCO_3-T$		1.073	0.932	9.08	—
magnetite		1.075	0.930	7.89	—
	600*	5.859	0.171	1.74	—
	800	5.167	0.194	2.60	—
$MgO-B$	1000	3.827	0.261	2.41	—
	1200	2.675	0.374	3.81	—
	1400	1.963	0.509	5.40	—
	600	2.157	0.464	2.30	0.699
	800	1.951	0.513	3.22	1.068
$MgO-A$	1000	1.935	0.517	3.79	0.515
	1200	1.812	0.552	2.44	0.304
	1400	1.620	0.617	2.69	0.368
carbon black		3.398	0.294	0.882	0.159

* numerals indicate the calcination temperatures.

The powders included in the latter group are $MgO-A$ and the carbon black. $MgO-A$'s are constituted of porous rod-like particles about 15 μ in length and 2 μ in diameter, and as these rod-like particles are floccules of fine particles, they are easy to break. Therefore, in the packing of these magnesium oxides, the packing of the rod-like particles may occur in the first step and, as the packing proceeds, in the second step the packing accompanied with the destruction of the rod-like particles may occur.

The carbon black is very easy to flocculate and makes many flocculated particles. Accordingly, the packing of the carbon black can be considered to have two steps, that is, the packing of the flocculated particles and that with the destruction of the flocculated particles.

From the above consideration we can assume that k corresponds to the packing process of the secondary particles or the flocculated particles, and that k' corresponds to the packing which is accompanied with the destruction of the flocculated particles.

In the powders which have no flocculated particle or have very fine flocculated particles, we can not find two steps in the packing process. Calcium carbonates and the magnetite are not so easy to flocculate and $MgO-B$'s have very fine porous plate-like particles of about 1 μ in diameter. Therefore, these powders show only one step in the packing.

The above consideration can roughly explain the experimental results, but more detailed experiments to confirm the consideration is desirable.

V. Packing in Liquids

Usually the packing studies are performed in dry states, but by tapping the powder settled in liquids and observing the change of its volume, we can learn the state of the powder in liquids.

Spherical glass powders which had been settled in liquids over night were tapped with the method given before, and the settling volumes or the sedimentation volumes and the final apparent specific volumes after the tappings are given in Table 4.

Table 4. Sedimentation volume and apparent specific volume of spherical glass powders in liquids. Falling height: 10 mm

medium (liquid)	sedimentation volume (*A*) or apparent sp. volume (*B*), cm^3/g	average particle diameter, μ			
		37.1	24.7	17.2	11.4
air	*B*	0.707	0.717	0.733	0.747
water	*A*	0.699	0.662	0.658	0.672
	B	0.663	0.660	0.662	0.671
ethyl-alcohol	*A*	0.698	0.661	0.661	0.693
	B	0·677	0.656	0.659	0.675
carbon tetra-chlorids	*A*	0.789	0.782	0.826	0.943
	B	0.672	0.678	0.685	0.723

As glass powder is polar and has strong affinity with polar liquids, its sedimentation volumes in water and in alcohol are smaller than those in carbon tetrachloride, in which the glass powder is considered to be flocculated.

When the settled powders are tapped, the volume of the powders in water and in alcohol shows a little or no change, but that in carbon tetrachloride decreases remarkably and finally takes nearly the same value as in water and in alcohol. From this we can conclude that the powder in carbon tetrachloride is deflocculated by the tapping and takes the same state as in water or in alcohol, that is, a dispersed state.

The final apparent bulk volume of the powder in liquids is smaller than that in air. This is due to the lubricating effect of the liquids.

The change of the apparent bulk density in liquids by the tapping also obey the relation given by Eq. (2). The values of constant k of the packing of spherical glass powders in carbon tetrachloride and in air are given in Table 5.

Table 5. Constant k for spherical glass powders in carbon tetrachloride and in air. Falling height: 10 mm.

average particle dia., μ	$k \times 10^2$	
	in air	in carbon tetrachloride
37.1	37.6	0.164
24.7	33.0	0.127
17.2	11.3	0.076
11.4	6.3	0.031

The values of k in carbon tetrachloride are about in the same order as the values of k' in Table 4. This coincidence suggests that the procedures corresponding to the steps expressed by k in Table 5 and k' in Table 4 are the same and both are the packing accompanied with the deflocculation of the flocculated particles.