

# Evaluation of flowability for granulated powder using a test of powder discharge by pressurized air

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**Abstract.** This study experimentally and theoretically examined the flowability and the cohesiveness for powder using a test of powder discharge through an orifice by the pressurized air. The powder used consisted of two kinds of Calcium hydroxide which have different particle sizes by granulation. These sizes are 11  $\mu\text{m}$  and 176  $\mu\text{m}$ , those called  $\text{Ca}(\text{OH})_2$  -A and -B. Cohesiveness is characterized by the Bond number which is the ratio of separation force to the gravity force. Flowability is evaluated by the relationship between the mass flow rate and the average air pressure acting on the powder bed. We found that the Bond number of  $\text{Ca}(\text{OH})_2$  -B was much lower than  $\text{Ca}(\text{OH})_2$  -A. The relation between the mass flow rate of the powder and the average air pressure indicates  $\text{Ca}(\text{OH})_2$  -B is easily flowing at the lower pressure region, and  $\text{Ca}(\text{OH})_2$  -A was scattered at the higher pressure region. This means  $\text{Ca}(\text{OH})_2$  -B has good flowability by the particle granulation in comparison with  $\text{Ca}(\text{OH})_2$  -A.

## 1 Introduction

Cohesive powders have become more commonly used in industrial processes because they have the advantage of superior reactivity due to their large specific surface area [1]. However, the handling of cohesive powder in the surrounding air is extremely difficult due to the influence of cohesive force, which is relatively strong in comparison to the gravity force when reducing the particle diameter [2]. For example, when the powder is discharged from a hopper or a silo, the bridge and the flooding of cohesive powders are encountered in these practical situations, and those troubles need to be avoided. Therefore, various operations to powder discharge have been proposed such as air injection, fluidization, mechanical vibration, and mechanical feeder [3]. As one of them, the micro feeding device of fine powder using a vibrating capillary tube has been developed [4]. Meanwhile, these phenomena such as bridging, flooding, and powder flowing in equipment are extremely related to the flowability of powder. It is therefore a very important subject to be considered in the evaluation of the flowability of the cohesive powder.

Regarding this subject, the previous studies [5-7] have been experimentally investigated the flow of powder through an orifice at the flat bottom by using the pressurized air to the powder bed which belongs to the group A and C particle in Geldart classification [8]. Results indicate that the continuous discharge of cohesive powder is obtained when the same flow rate of air has been supplied at the top and the bottom of the powder bed in a vessel. Furthermore, it was considered the different flow pattern of the powder bed depends on the location of the supplied air. These studies also

indicated the influence of the void fraction and the interstitial air pressure on the beginning of powder discharge from an orifice and the continuous discharge which is expressed by the mass flow rate of the powder. However, it has also been observed that a few powders could not discharge by using the air pressure to the powder bed when the influence of the cohesive force was still strong. Hence, we noticed the flow of cohesive powder and air during the powder discharge is influenced greatly by the void fraction and the force acting on the particle. Therefore, the evaluation of the flowability of cohesive powder in air is extremely important due to the above reasons.

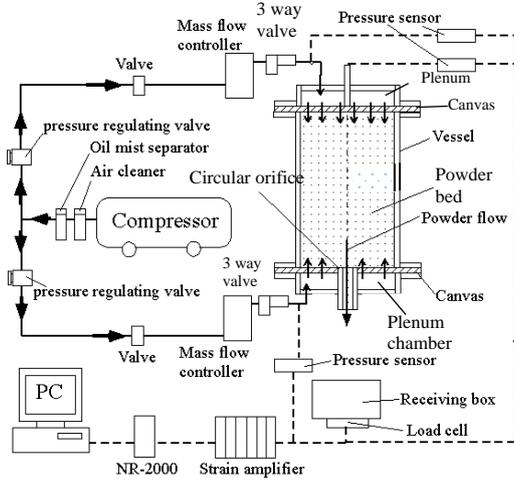
There are numerous flowability tests of powder [9], and Carr's index [10-12] has been applied to evaluate the flowability using the powder tester [13]. Recently, new methods for the evaluation of flowability have been also proposed [14]. However, the flowability and the cohesiveness are not being evaluated simultaneously by the previous method when the powder flows with the air. Therefore, we have experimentally investigated flowability and cohesiveness of the cohesive powder, having different particle diameters, discharging it by air pressure for different initial void fraction and flow rates of air [15, 16]. In this study, we experimentally and theoretically examined the flowability and the cohesiveness of two kinds of Calcium hydroxide having different sizes due to particle granulation. The cohesiveness is evaluated by the Bond number which is the ratio of separation force to the gravity force. The flowability is also evaluated using the relationship between the mass flow rate of the powder and the average air pressure acting on the powder bed.

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## 2 Experiment

Figure 1 shows a schematic diagram of the experimental equipment to evaluate the flowability and the cohesiveness of the cohesive powder by using pressurized air.



**Fig. 1.** Experimental apparatus.

The experimental equipment consists of the filling part of the cohesive powder and the air supplying section at the top and the bottom of a vessel. The powder filling vessel was made by a cylindrical acrylic pipe which has an internal diameter of 50mm and a height of 150mm. The air distributors that are used to generate the uniform air supply were arranged at the top and the bottom of a cylindrical vessel. The air from the compressor was introduced through the three-way valve and the air was simultaneously supplied from distributors to the powder bed in the vessel. By using this operation, the powder in the vessel can be discharged from a circular orifice of 4mm diameter at the center of the bed bottom. The flow rate of air from the top and the bottom of the powder bed in the vessel was adjusted by the mass flow controller. The discharged mass of the powder through an orifice was measured by the load cell which is installed at the bottom of a receiving vessel. The measurement of the air pressure acting on the top of the powder bed was also done using the pressure sensor which is located at 150mm from the bottom of the vessel. The initial height of the powder bed  $H$  was registered to estimate the initial void fraction.

Table 1 indicates the material properties of the two samples of Calcium hydroxide that have different particle diameters and the same material density.

These powders are called  $\text{Ca(OH)}_2$  -A and  $\text{Ca(OH)}_2$  -B in this study. In the experiment, the particle diameters were measured by the dry method of the particle size analyzer. Furthermore, for both powders, Carr's flowability index  $FW$  was measured using a powder tester of Hosokawa micron. The values obtained for  $\text{Ca(OH)}_2$  -A and B were, respectively, 36 and 43 as shown in Table 1. According to the evaluation of Carr's index,  $\text{Ca(OH)}_2$  -A and  $\text{Ca(OH)}_2$  -B were respectively classified as "Bad" and "Not good".

**Table 1.** Particle properties and experimental conditions.

Powder	$\text{Ca(OH)}_2$ -A	$\text{Ca(OH)}_2$ -B
$x_p$ [ $\mu\text{m}$ ]	11	176
$\rho_p$ [ $\text{kg/m}^3$ ]	2240	2240
$FW$	36	43
$M_{pi}$ [g]	70	70
$H_i$ [mm]	103~108	73
$\varepsilon_i$ [-]	0.836~0.844	0.762
$Q_t=Q_b \times 10^{-5}$ [ $\text{m}^3/\text{s}$ ]	1.3~2.5	0.067~1.5

Additionally, these powders belong to group B and C particles in the Geldart classification [8].

Table 1 also shows the experimental condition in the present study. The initial filling mass of powder in a cylindrical vessel was fixed at 70g. The flow rate of air from the top and the bottom of the powder bed in a vessel varied from  $0.067 \times 10^{-5}$  to  $2.5 \times 10^{-5} \text{ m}^3/\text{s}$  which given the different air pressure to the powder bed. Two kinds of powder were filled naturally in a cylindrical vessel. Then, the initial height of the powder bed was measured by a scale because it is needed for the calculation of the initial void fraction in all the experimental conditions. The initial void fraction  $\varepsilon_i$  was calculated using the following equation.

$$\varepsilon_i = 1 - (\rho_b / \rho_p) = 1 - (4M_{pi} / \pi D_v^2 H_i \rho_p) \quad (1)$$

where  $M_{pi}$  is the initial mass of powder,  $D_v$  is the internal diameter of a cylindrical vessel,  $H_i$  is the initial height of the filling powder and  $\rho_p$  is the material density.

## 3 Results and discussion

The cohesiveness of powder was evaluated, like our previous study [16], by the Bond number  $Bo$  [17] which is the ratio of separation force to the gravity force.

The separation force acting on particle  $H$  was considered by the air pressure acting on the powder bed, and estimated based on the Rumpf equation [18, 19] as indicated in Eq. (2), where  $\sigma$  is the stress acting on the powder bed,  $x_p$  is the mean particle diameter,  $\varepsilon$  is the void fraction and  $k$  is the coordination number [20]:

$$H = \sigma \pi x_p^2 / (1 - \varepsilon) k \quad (2)$$

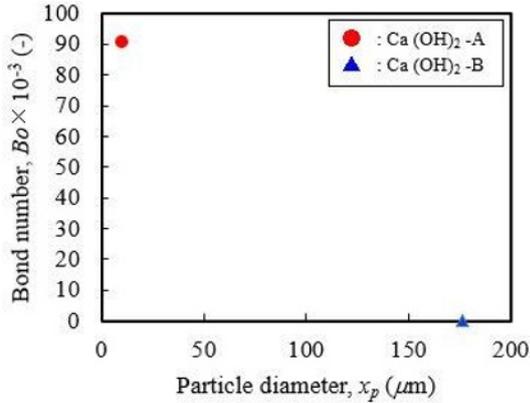
$$k = 13.8 - \sqrt{175 - 232(1 - \varepsilon_i)} \quad (3)$$

In this study, the stress and the void fraction were substituted as  $\sigma = p_s$ ,  $\varepsilon = \varepsilon_i$ . Therefore, the Bond number  $Bo$  [20] is obtained as shown in Eq. (4). In the equation, the gravity force  $F_g$  was put with  $(\pi/6)\rho_p x_p^3$ .

$$Bo = \frac{H}{F_g} = \frac{6p_s}{\rho_p g x_p (1 - \varepsilon_i) (13.8 - \sqrt{175 - 232(1 - \varepsilon_i)})} \quad (4)$$

Fig. 2 shows the relationship between the Bond number  $Bo$  and the particle diameter  $x_p$  of  $\text{Ca(OH)}_2$  -A and B. The air pressure at the beginning of the powder discharge has chosen the lowest value to each powder because the Bond number is the threshold value to the powder flow which transfers from the static to the

dynamic states. The result clearly distinguished that the Bond number of  $\text{Ca(OH)}_2$  -B shows an extremely lower value compared to  $\text{Ca(OH)}_2$  -A. It is inferred that the particle size influenced the powder flow and the cohesiveness. Furthermore, the Bond number of  $\text{Ca(OH)}_2$  -A became about 460 times against  $\text{Ca(OH)}_2$  -B. Hence, the cohesiveness by the comparison with the Bond number was classified as follows:  $\text{Ca(OH)}_2$  -B <  $\text{Ca(OH)}_2$  -A.



**Fig. 2.** Relation of the Bond number and the particle diameter.

In general, the flowability of powder represents how the powder flows easily. This means that the flowability in this study would be evaluated by using the flow of powder discharge from an orifice at the bottom of a vessel. Furthermore, the air pressure and the void fraction are influenced by the flow of cohesive powder. Therefore, the mass flow rate of powder from an orifice as a function of the air pressure and the initial void fraction can be used to evaluate the powder flowability [16]. The powder flowing model, based on previous studies [16, 21-23], is shown in Eq. (5):

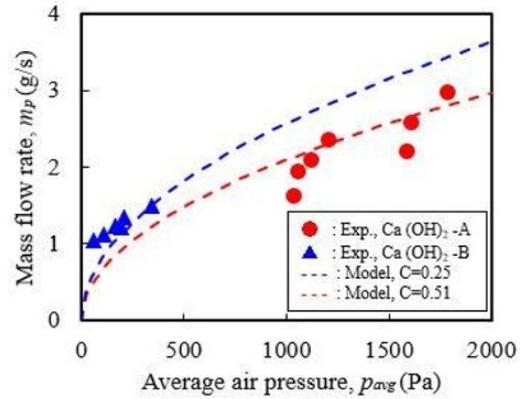
$$m_p = C \frac{\pi}{4} (D - k_p x_p)^2 \sqrt{2(1 - \varepsilon) \rho_p p_a} \quad (5)$$

where  $m_p$  is the mass flow rate of powder,  $D$  is an orifice diameter,  $x_p$  is the particle diameter,  $p_a$  is the air pressure acting on the powder bed,  $\rho_p$  is the material density,  $\varepsilon$  is the void fraction,  $C$  is the discharge coefficient and  $k_p$  is the shape coefficient of particle. When the known values of the above parameters are substituted in Eq. (5), the mass flow rate can be expressed as a function of the air pressure, the void fraction, and the discharge coefficient as shown in Eq. (6). The initial void fraction  $\varepsilon_i$  and the averaged air pressure  $p_{avg}$  were used in the analysis.

$$m_p \propto C \sqrt{(1 - \varepsilon_i) p_{avg}} \quad (6)$$

Fig. 3 shows the mass flow rate of  $\text{Ca(OH)}_2$  -A and B against the average air pressure at the top of the powder bed where the initial void fraction of each particle is shown in Table 1. Dischargeable and transition flows were selected as the plotted data. The dotted line indicates the estimated mass flow rate which is calculated by Eq. (5), and the discharge coefficient of these lines is 0.25 and 0.51, respectively. In Fig. 3, the mass flow rate of  $\text{Ca(OH)}_2$  -B increased gradually with

increasing the average air pressure at the top of the powder bed.



**Fig. 3.** Relationship between the mass flow rate and the average air pressure at the top of the powder bed.

The result indicated that the mass flow rate of B powder was closed to the estimated mass flow rate of Eq. (5). It is inferred that the powder flow is similar to the liquid flow due to the reduced cohesiveness as shown in the result of Fig.2. On the other hand, the mass flow rate of  $\text{Ca(OH)}_2$  -A was scattered against the average air pressure in comparison with B powder. This means that the flow of  $\text{Ca(OH)}_2$  -A indicated the unsteady, and then it is inferred the powder has received the effect of strong cohesiveness as well as the result of Fig.2. These results found that the flowability of two kinds of Calcium hydroxide powder can be evaluated by using our tester as follows:  $\text{Ca(OH)}_2$  -A <  $\text{Ca(OH)}_2$  -B. Furthermore, the evaluation of flowability to two kinds of powder in this study has the same tendency as Carr's flowability index as shown in Table 1. It is therefore concluded that our suggested method can be used to evaluate the flowability of powder.

## 4 Conclusion

This study examined the evaluation of the flowability and the cohesiveness of two kinds of Calcium hydroxide using the powder discharge by the pressurized air.

The cohesiveness of two kinds of Calcium hydroxide was estimated by the Bond number which expresses the ratio of separation force to the gravity force. The result found that the Bond number was lower when the particle diameter was large due to the granulation. Meanwhile, when the particle diameter was small without the granulation, the Bond number indicated an extremely higher value. This result suggested that the cohesiveness was classified as follows:  $\text{Ca(OH)}_2$  -B <  $\text{Ca(OH)}_2$  -A.

The flowability of the two kinds of Calcium hydroxide was evaluated by the relation of the mass flow rate and the average air pressure acting on the top of the powder bed. The mass flow rate of powder increased gradually with increasing the average air pressure at the top of the powder bed when the particle diameter was large due to the granulation. On the other hand, the mass flow rate of smaller particle diameter was clearly scattered against the average air pressure. It is therefore

supposed that the flowability of a test of powder discharge by the pressurized air is also classified as follows:  $\text{Ca(OH)}_2\text{-A} < \text{Ca(OH)}_2\text{-B}$ .

As a result, it is concluded that the high cohesiveness powder presented a lower flowability, and the cohesiveness is linked to the flowability of the powder with airflow. Therefore, particle granulation is one of the important operations to be considered to improve the flowability of the cohesive powder.

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