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Experimental investigation on granular fodder flow characteristics during discharge period in silo

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Abstract

The purpose of this study is to conduct an experimental investigation on granular fodder flow characteristics during discharge period in silos. The pressure on the silo wall and the mass flow rate of pellets feed stored in the silo for 1 hour were determined with the laboratory-scale steel and fiberglass silos. Additionally, the parametric study of four angles of a 55 mm diameter outlet conical hopper such as 10, 20, 30, and 45 degrees were done in this testing. From the results, the average wall pressure of the steel silo in the discharge period was more than that of the fiberglass silo. Both silos presented the minimum and maximum mass flow rate occurring on a hopper angle of 45 degrees and 10 degrees, respectively. When considering experimental results of the wall pressure and the average mass flow rate, it could be concluded that the flow patterns of granular fodder during discharge period in both steel and fiberglass silos were funnel flow patterns.

Keywords: Discharge process, Granular fodder flow, Pattern flow, Silo

1. Introduction

The feed industry is an agricultural processing industry that uses silos to store the granular product. Most silos in this industry are a cylindrical silo with conical hopper as shown in Figure 1.

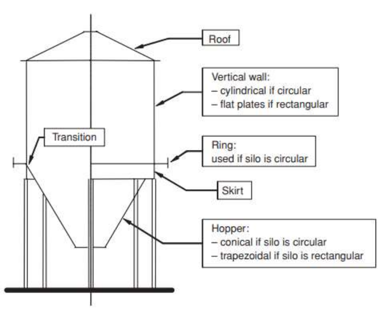


Figure 1 Terminology for parts of a hopper silo. (Rotter, 2009)

However, in the process of waiting for transportation, it was found that the feed stored in silos for a long time can be introduced to blockage of flow above the silo exit channel during discharge process. In other words, the material can flow out for a certain period of time, and then jamming occurs stagnant or immobile. This is the primary issue causing significant damage to the feed industry. As the result, various technologies are being employed to assist in the resolution of this issue. For example, some devices are installed to allow vibrating, taping, or shaking on the silo. Additionally, the usage of blowing wind for destroying the material's adhering ability is implemented. Many industrial silos have been damaged by popular solutions such as knocking from the outside with a heavy hammer for breaking down the material that sticks together and allowing it to move out as shown in Figure 2.

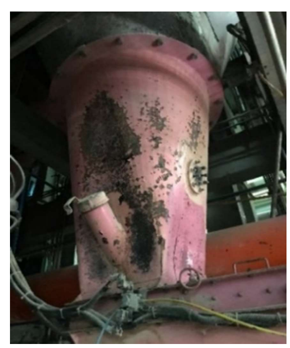


Figure 2 Hammer rash.

There are two main processes of material flow within the silo as filling process and discharge process. When the outlet is opened, the material begins to gravitationally move out of the silo. The movement of objects could be classified into three flow patterns: mass flow, funnel flow, and expand flow as shown in Figure 3. For the mass flow, it is defined that all the material inside the silo was constantly moving out of the silo. The formation of this flow pattern is introduced in hoppers with small tilt angles and sufficiently smooth silo walls. There are no areas that cause an abrupt change in the direction of movement. Hence this type of flow pattern is suitable for the operation of industrial silos and considerable to be the best flow pattern (Grudzien & Gonzalez, 2013). Unlike the funnel flow, material located only in the center of the silo is allowed to move out while some material is fixed to the silo wall. This phenomenon creates dead zones within the silo. In the case of a combination of the two flow forms, only the material located in the core bin region and the hopper area are all material outflow phenomena.

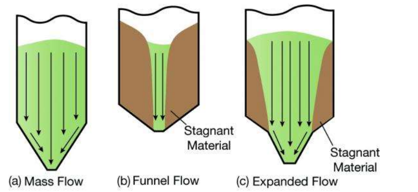


Figure 3 Flow pattern a) Mass flow b) funnel flow and (c) Expanded flow**.** **(**Greg Mehos et al., Apr 2018)

As mentioned above, the design of silos with effective particle outflow could clearly be one of the high-priority improvement issues in the feed industry. In engineering design, it is necessary to consider the pressure inside the silo and the maximum force exerted on the wall, combined with the mass flow rate due to the material flowing out, it is used to analyze mass flow/funnel flow behavior in bins or hoppers. (Askegaard & Munch-Andersen, 1985; Ayuga, Guaita, Aguado, & Couto, 2001; Härtl et al., 2008; Ramírez, Nielsen, & Ayuga, 2010; Zhong, Ooi, & Rotter, 2001)**.** Uñac et al. (Uñac, Vidales, Benegas, & Ippolito, 2012) conducted an experimental study of the influence of different silo-shape factors and outlet sizes that affect the mass flow rate of quartz particles. The result of the study has shown that the channel size factor significantly affects the flow rate, as well as Wang et al. (Wang et al., 2022) studies the flow patterns of barre and plastic pellets, and the pressure at the flat bottom aluminum silo walls, which changes the flow pattern from a funnel flow to a mass flow. The result of the study has shown that the filling process strongly affects the flow pattern and pressure of the pellets, while the barre is only slightly affected. In addition, Wang et al. (Wang et al., 2020) also studied the pressure created during the flow process of mass-volume materials in an experiment with conical silos. The result of the study found that the stress fluctuation at the hopper top is independent of the outlet diameter, while the period of the stress fluctuation decreases with the increase of the outlet diameter. As well, many researchers conducted studies on the pressure within silos during the discharge process of various materials (An, Wang, Fang, Liu, & Liang, 2021; R. Gandia, Júnior, Carlos Gomes, Coimbra de Paula, & Dornelas, 2021; R. M. Gandia, Gomes, Paula, Oliveira Junior, & Aguado Rodriguez, 2021; Tang, Lu, Guo, & Liu, 2021; Walker, 1966) to guide the design of silos for further maximize efficiency. However, a few researchers are considering the flow of feed materials in silos. Hence, this research project aims to conduct an experimental study of the pressures that occur in silo walls and the mass flow rate of fodder preserved in a silo for 1 hour during the discharge process. The testing silos, moreover, are made of steel and fiberglass which have a conical hopper with an outlet diameter of 55 mm and an inclination of 10, 20, 30, and 45 degrees.

2. Materials and methods.

2.1 Fodder

The fodder product used in the test was manufactured by CPF (Thailand) Public Company Limited. The bulk density was 444.45 kg/m^3, the average diameter was 2 mm and the average length was 5 mm. The moisture content was 13% on average; it was evaluated by a moisture analyzer and can be used to accurately determine the moisture content in feed samples. In each trial, the amount of fodder was 15 kg as shown in Figure 4.

Figure 4 fodder material.

2.2 Characteristics of laboratory-scale silos

The laboratory-scale silo was divided into two parts: a bin and a hopper with varied inclination angles of 10, 20, 30, and 45 degrees as well as an outlet size of 55 mm as seen as Figure 5.

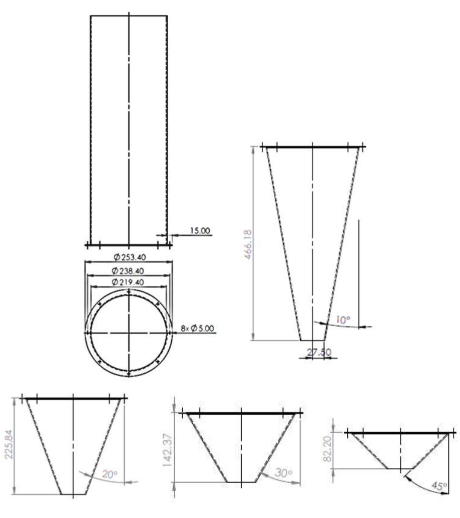


Figure 5 The scale of the silo laboratory

Testing silos were made from steel and fiberglass materials which were based on feed industrial silo's characteristics. The one-tenth size scale reduction of an actual industrial silo was applied to this experiment. The characteristics of testing silos are illustrated in Figure 6 .

a)

b)

Figure 6 Laboratory-scale silos: a) Steel silo b) Fiberglass silo.

2.3 Laboratory set-up

The two main measuring instruments were installed on the test rig such as the load cell for measuring the material weight and the force sensing resistors (FSR) for measuring normal pressure acting on the wall during the discharge process. Three load cells with a weight range from 0 to 50 kg were equipped to measure the weight of the changing feed as shown installation points in Figure 7.

Figure 7 Location of three load cells.

The bin wall and hopper wall of lab-scale silos were attached with Force Sensing Resistors (FSR) which is able to withstand pressures of 0 kg to 10 kg and had a specification of sensitivity range < 1.5 psi to > 150 psi (0.1 to 10 kg/cm^2). Hoppers with inclination angles of 10, 20, 30, and 45 degrees faced the installed instrument points as seen in Figure 8.

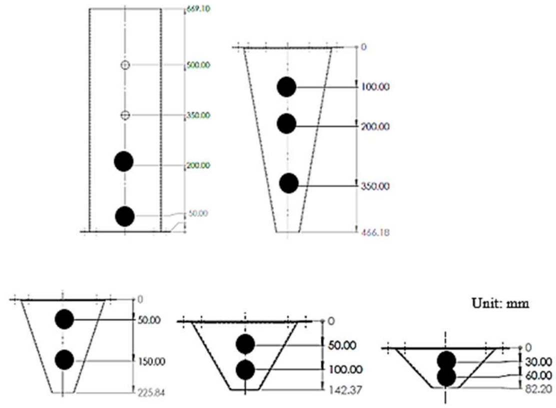


Figure 8 Location of FSR on various hoppers

2.4 Parameter

2.4.1 Normal pressure acting on the silo wall

After filling the material in a silo and storing for 1 hour, the experimental data is obtained while opening the silo's exit channel to allow the material to flow out. The reading data obtained from the pressure sensor mounted on the storage tank and hopper wall is introduced to Eq. (1) This would be as a weight value that can be used to calculate the pressure.

$$P = \frac{F}{A} \tag{1}$$

where P - Normal pressure on silo wall (kPa)
F - Force of fodder obtained from FSR (N)
A - Area of FSR equal to 0.001452 m^2

2.4.2 Mass flow rate

The process of collecting data to calculate the mass flow rate of material can be done in conjunction with pressure-finding experiments at the silo wall. The load sensor monitors the weight of the material being released at any point in time and the average mass flow rate (Q) is obtained by dividing the weight difference of the fodder by the time it takes out the complete. This equation could be expressed as Eq. (2)

$$Q = \frac{|w_1 - w_2|}{|t_1 - t_2|} \tag{2}$$

where Q - Average mass flow rate (kg/s)
w_1 - Weight of fodder at t_1 (kg)
w_2 - Weight of fodder at t_2 (kg)
t_1 - Time (s)
t_2 - Time (s)

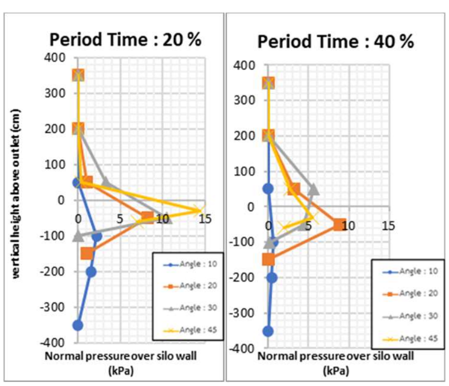
3. RESULT AND DISCUSSION

This study considers the pressure on the silo wall and the mass flow rate of the material during the discharging process. The experiment was repeated three times at 32˚c, showing the following results.

3.1 Normal pressure acting on silo wall

The pressure data on the wall of bin and hoppers made of steel and fiberglass with tilt angles of 10, 20, 30 and 45 degrees obtained during the release process are considered in percentage time periods of flow time and presented in Figure 9 and Figure 10, respectively.

From Figure 9, shows the result of normal pressure over the steel wall, it was found that the characteristic of normal pressure greatly depended on the hopper's degree of inclination. Considering the second to fourth period on the release procedure reaching its finish, it is observed that hoppers with an angle of inclination of 10 degrees result the lowest pressure, compared to other hoppers at all places of measurement. It can be seen from the first period that the value of normal stress with hoppers at 10, 20 ,30 and 45 degress are 2.2, 8.3, 10.8, and 14.4 kPa, respectively.



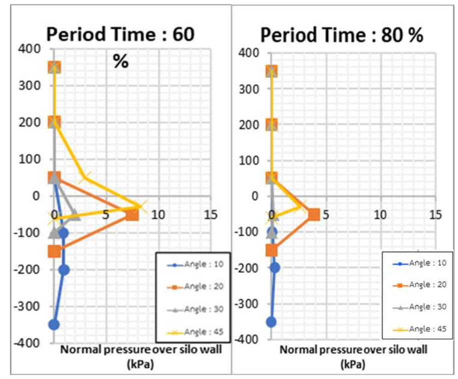


Figure 9 Normal pressure over the steel silo wall with different hopper inclination angles.

When evaluating pressure fluctuation, it is reported that it mostly happens with hoppers at a 45 degree angle of inclination, the result shows that the normal pressure increases at the beginning, then decreases in the second period, then increases in the third period, and finally drops obviously.

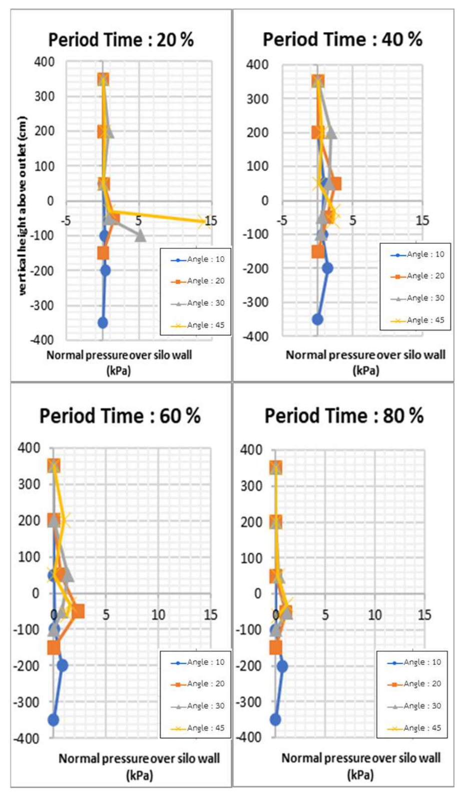


Figure 10 Normal pressure over the fiberglass silo wall with different hopper inclination angles.

From Figure 10, it is found that, at the first period, the pressure varies according to the size of the hopper's angle of inclination and it is noticeable that the results obtained from hoppers with a 10 degree inclination angle present the minimal pressure compared to other size hoppers in all positions of measurement, as well as steel silos. Moreover, similar results are shown when considering the profile of pressure exerted on steel and fiberglass silos. There is the area of the highest pressure under the seam between the bin and the hopper. Then it gradually decreases as it approaches the exit channel. However, the value of pressure generated at the walls of the fiberglass silo is lower than that of the steel silo.

3.2 Mass flow rate

Experiments presented the results obtained from steel hoppers with an angle of inclination of 10 degrees being the highest average mass flow rate of 1.006 kg/s. When comparing the flow rate between steel hoppers and fiberglass, it was found that the testing of steel hoppers showed a higher mass flow rate than the testing of fiberglass hoppers in all values of inclination angle as seen in Table 1. It is because of silos made of steel have better finishing and smoother surfaces than silos made of fiberglass at the experimental time. However, after a given amount of time, the surface of the steel material may corrode, then it causes a decrease in flow rates.

Table 1 Average mass flow rate.

Inclination of hopper (Degrees)	Average mass flow rate (kg/s)		% Diff
	Steel	Fiberglass	
10	1.006	0.677	32.70
20	0.687	0.428	37.70
30	0.472	0.316	33.05
45	0.257	0.238	7.93

It was also found that steel hoppers with an angle of inclination of 45-degrees formed an arch of material above the exit channel and it results in a stoppage of flow as shown in Figure 11. Therefore, a knock was done on the outer wall to facilitate the flow. After that, the material was able to flow out continuously until a material collapse caused the weight of the material to drop sharply. While fiberglass hoppers were non-jammed and gave an average flow rate of 0.238 kg/s, with the reason that the wall friction between particles and fiberglass is lower than that (Santhisan K., Kraitong K. , & Kanokjaruvijit K. , 2022). It is a function of the stress level applied to the wall surface. The wall friction angle is an important parameter; it is used to determine behavior in bin and hopper.

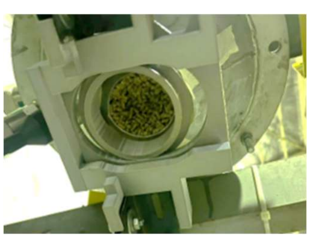


Figure 11 Flow blockage in hopper.

Arching happens when a sufficiently cohesive powder is stored in a hopper that has not steep enough cone walls and/or a large enough outlet. It could be avoided by design by calculating the hopper wall angle required and the critical outlet diameter required in order to always ensure enough constraint to break arches and make the powder flow.

4. CONCLUSION

In all studies, it is discovered that silos made of steel had greater pressure values on the silo wall in the discharge process of fodder materials than silos made of fiberglass and the pressure value varies according to the size of the hopper's angle of inclination. It means that when the hopper has a greater angle of inclination, the pressure becomes greater accordingly. However, it is found that the average mass flow rate of steel silos is higher than that of fiberglass silos. This is due to the factor of the internal surface since the steel silos used in the experiment are newly manufactured and unprocessed. Whereas fiberglass silos have a rougher surface, it is discovered that hoppers with a 10-degree angle of inclination produce the maximum mass flow rates from both steel and fiberglass silos of 1.006 kg/s and 0.677 kg/s, respectively. Also, when considering the effect of the pressure pattern combined with the average flow rate of the material, it could be said that the flow characteristics of fodder in silos which steel and fiberglass produced would be in a funnel flow pattern. In conclusion, the steel silo has better than the fiberglass silo for materials stored for 1 hour.

5. ACKNOWLEDGMENT

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