Comparison of Methods for Measuring Powder Flowability

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Abstract

Powders are widely used in pharmaceutical applications and understanding their nature is an important aspect of making successful formulations. Powder flowability describes the behaviour of powders and can be measured using several different methods. This study looks at the techniques: angle of repose and tapped density, comparing them to each other and looking at how consistent they are with changing variables, such as container size, powder mass, and number of taps for the tapped density tests. Tests were performed using several different powders, such as different forms of sodium bicarbonate and lactose. Results show a dependence of powder flowability on particle size of the powders involved. Granulated lactose exhibited great flowability through all the tests. Container size is shown to have little to no effect on the results, while the number of taps has a big influence on the tapped density results. Good flowing powders have overall coherent results, while poor flowing powders are affected by changes in experiment design to a greater degree. Angle of repose and tapped density measurements can give rough estimates for powder flowability, but do run the risk of inconsistent results based on the physical parameters of the experiment.

Content

Introduction

Powders are used everywhere in manufactured products, and understanding and controlling their behaviour is very important in the manufacturing processes. The behaviour of solids, liquids and gases are fairly well understood and can be predicted mathematically, but powders are bulk materials and essentially an assembly of all three states; the powder particles are solids, liquids may be present inside or on the surface of the particle, and air is present between particles. Bulk characteristics, such as flowability, are consequently affected by the interaction of all these three parts. Furthermore the powder's characteristics are influenced by the properties of the particle itself, such as size, size distribution, shape, surface texture, cohesive and adhesive effects etcetera. External conditions such as consolidation, humidity, equipment surface material, will also affect the powder behaviour and need to be taken into account. Understanding these things in regards to manufacturing processes and the choice of equipment is a key to a high quality product. [1]

Aim

The aim of this master thesis is to investigate how selected powder flowability measurement methods are affected with changing variables. The methods studied are angle of repose and tapped density, in regards to variables such as powder mass, powder type and more. Data was collected for several different powders, including lactose, sodium bicarbonate, sand and cellets.

Theory

What is a powder?

Defining the fundamental concept of powders is the first step in understanding their function and behaviour. As stated above powders are bulk materials where all three material states are present at the same time - vapour, liquid, solid as illustrated in Figure 1 - but the identifying property is the powder particles. Without powder particles there is no powder. The particles can have the same or different chemical compositions from each other, but should have similar, comparable diameters of 1000 µm or less. If the powder particles are larger, or if smaller particles have grouped together into larger structures, with equivalent dimensions ranging from 0.2 to 4 mm they are referred to as granules. Granules will still behave as a powder. [2]

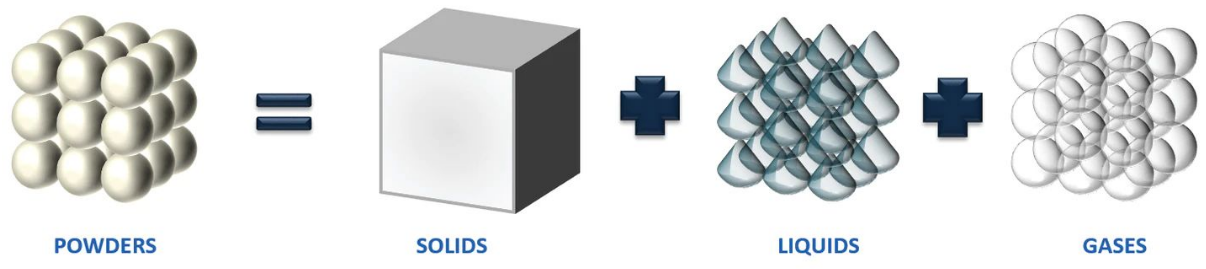

Figure 1 Powder consists of solids, liquids and gases at the same time. [E]

Flowability of Powder

Why is investigating powder flow important? In terms of pharmacological products, powder is very often a part of the manufacturing process in one way or another, and understanding the flow properties leads to uniformity of the product. Containing uniform flow:

- results in consistent tablet weight, through controlled particle packing,
- creates reproducible conditions, which further contributes to uniformity in the final product,
- limit entrapped air in the powder or tablet, avoiding undesired effects such as tablet capping and fragmentation,
- decreases excess powder in the tableting machine, which could otherwise cause lubrication problems and increased dust contamination.

Combined, this enables a higher production rate with high quality end products, such as uniform and marketable tablets. [1][2] [7]

Powder flow can be classified as certain types based on the force or energy applied: 1) Gravitational flow, as the name suggests, is when powder flows or falls under the influence of gravity e.g. through an orifice. 2) Mechanically forced flow can be studied looking at torque via rotary devices, such as rotary viscometers. 3) Compression flow is studied through looking at the (change of) volume of a powder bed in relation to an external pressure. 4) Vibration flow can be studied with a vibration powder tester, and arises from vibration being able to change the packing structure of the powder bed. [3]

As we've already discussed the properties of the particle will affect the ease of flow, but flowability is also very dependent on particle interactions and the mechanisms of those may restrict particle movement. The only real promoting force is gravitation and comparing that to the collected restrictive forces gives an idea if particles will move independently or form agglomerates. Interparticle friction is an example of a restrictive force arising from rougher surfaces. If we look not only on the particle surface, but also on the particle shape we can have mechanical interlocking caused by larger scale, uneven features. The presence of liquids on the particle surface will also act as binding and cause particles to stick together. In addition to these particle interactions, we also have cohesion and adhesion, two facets of the same phenomenon. Cohesion - between similar surfaces - and adhesion - between different surfaces - are attractive forces acting between powder particles, or between particles and container surfaces. They consist mainly of short-range van der Waals forces, and vary depending on particle properties. [1][2][3]

Measuring Flowability

For measuring flowability there are four traditionally used options. Angle of repose is one of these, and possibly the simplest. The powder is poured through a funnel and settles on a flat surface underneath. Interparticle forces will result in different angles, measured between the horizontal line and the slope of the powder pile (see Figure 2). This gives a way to infer and classify how the powder will flow. The advantages to this method are that it is quick, simple and cheap. Though there are several drawbacks as well; the variables of the method are not standardized, i.e. the height to the funnel from the base may be varied *or* constant, the base may be of a fixed diameter or open allowing the powder pile to spread. It is also somewhat dependent on operator technique and equipment used, as well as on aeration, consolidation and segregation in the funnel. Multiple angles can form in a single pile, making a determination of flow more complex. [2][4]

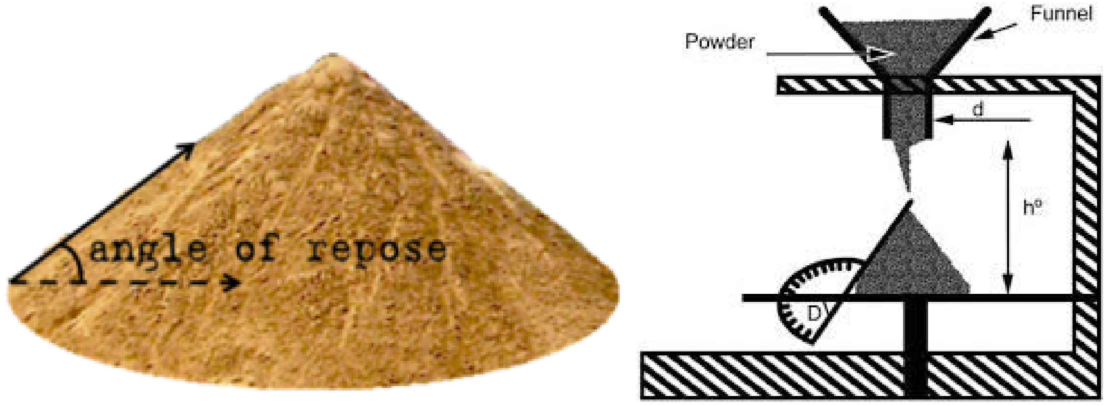

Figure 2 The angle measured in angle of repose tests, as well as a schematic view of an angle of repose measurement with an open base and fixed height. [A][D]

Flow through an orifice is a slightly more refined method than angle of repose, though this too has disadvantages, similar to angle of repose. Instead of measuring the angle, this method focuses on the rate with which the powder flows through a funnel or orifice with well-defined dimensions. This method can give continued (flow rate over time) or discrete measurements and comparatively over several different orifice diameters. Like angle of repose it is quick and low cost, but it is also dependent on the operator, e.g. how the powder is loaded into the vessel. Since the orifice diameters are usually small, it also has limited use when it comes to more cohesive powders. [2][4]

Tapped density is a third method, which looks at the related parameters of Carr's Compressibility Index (CCI) and Hausner Ratio (HR):

$$CCI = \frac{\rho_t - \rho_p}{\rho_t} \; x \; 100 \quad ; \quad HR = \frac{\rho_t}{\rho_p}$$

where ρ_t is tapped density and ρ_p is poured density.

The method of tapped density depends on the properties of a bulk sample of the powder. When the powder vessel is tapped a number of times the powder will settle, and the volume and density will change. This change is dependent on the cohesion and forces between the particles and measuring the differences between original and tapped powder gives an estimate for flow as per the equations above. This is a relatively low cost method, but its repeatability is affected by filling methods and the nature of the tapping (frequency and amplitude may vary). If the powder does not achieve a level surface at the starts of the experiment, accuracy of measurement may also be affected. [2][4]

Shear cell analysis deals with consolidated powders and measures the force it takes to shear one powder plane relative another. There are several different types, such as translational, annular and rotational shear cells (see Figure 3). This procedure gives better control of the environment of the experiment. It works well with consolidated powders under moderate to high stress, but not as well with low stress levels. [2][4] This study was not performed using shear cell analysis, due to lack of access to relevant equipment.

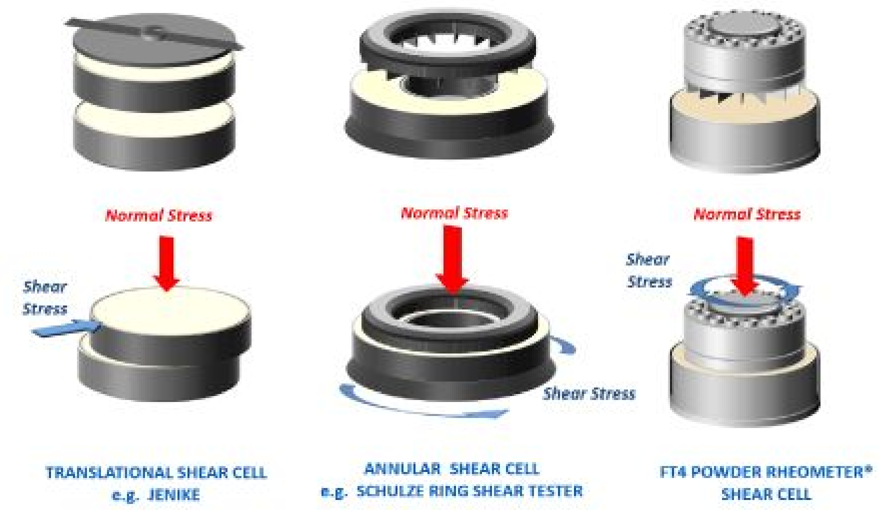

Figure 3 Examples of Shear Cell variants. [B]

Other tests methods have evolved from these four standardized ones, in attempts to refine the results and work away from the disadvantages presented above. Such as dynamic powder flow testing which works by measuring forces, axial and rotational, on a blade as it is rotated through a powder sample. This is more well-defined than the traditional methods and gives higher repeatability and sensitivity. The data may, on the other hand, be more difficult to interpret as it is a more complex method, and the equipment more expensive, thus availability can become a problem. [4]

Scientists also want to work towards needing smaller samples, as in the development of pharmacological products large bulk samples may not always be available. One such method, which requires 1 to 2 grams of powder, consists of a simple system of flow chamber, electronic balance and an automated optical detection system. [5]

Why is there not one standard test?

Powders are complex and they are used in complex systems. Powder behaviour depends on many different parameters and, today, there is no ultimate testing method that can incorporate testing all those. The different techniques currently used characterize slightly different properties of the powder, and to give a more complete picture of the dynamic facets of powder flow a combination of methods should probably be used. [6]

Powder used in this study

Four different powder substances were used in this study - lactose, sodium bicarbonate, cellets and sand - and in total thirteen variations and combinations of those were used in tests, as listed in the Materials & Methods section.

One of the powders was lactose, both granulated and non-granulated. Lactose is a disaccharide, naturally occuring in the milk of mammals and commonly used in the dairy industry. In the pharmaceutical industry, lactose is commonly used as filler in tablets, due to it being cost effective, has little to no taste, is water soluble and other advantageous factors. [8]

Sodium Bicarbonate is an antacid used for e.g. heartburn. If mixed with an acidic agent it will produce carbon dioxide, causing the fizzing present in effervescent powders. [9][10]

Cellets are pellets of microcrystalline cellulose used in controlled release formulations, drug layering and coating processes. Cellets are water insoluble and have an advantageous inert behaviour. [11][12]

The sand, from Lomma Beach, Sweden, does not have any pharmaceutical applications, but was instead chosen because of its particularly fine nature offering a greater diversity in characteristics among the used powders.

Scale of Flowability

Based on angle of repose or tapped density measurements, powders can be categorized on a flowability scale, indicating overall flow characteristics, as showcased by Figure 4.

Flow character	Angle of repose (θ)	Compressibility index (%)	Hausner's ratio
Excellent	25–30	≤10	1.00–1.11
Good	31–35	11–15	1.12–1.18
Fair	36–40	16–20	1.19–1.25
Passable	41–45	21–25	1.26–1.34
Poor	46–55	26–31	1.35–1.45
Very poor	56–65	32–37	1.46–1.59
Very, very poor	>66	>38	>1.60

Figure 4 Reference table when deciding powder flowability after angle of repose or tapped density measurements. [C]

Materials and Methods

Materials

Testing was done on lactose powder, granulated lactose powder, cellets, sodium bicarbonate and sand. Testing was also done on lactose and granulated lactose with a different water activity. The sodium bicarbonate was tested in three different variations; fine, standard and ultra-course, as well as combinations of the three. The sand was collected from Lomma Beach in Sweden.

List of Powders and Mixtures Used in this Study

The lactose comes from Fisher Scientific UK and the Sodium Bicarbonate from Brunner Mond and Company. Any granulation, conditioning, mixing et cetera were done at Lunds University in conjunction with this study.

- Lactose
- Lactose with higher water activity
- Granulated lactose
- Granulated lactose with higher water activity
- Sodium Bicarbonate (fine)
- Sodium Bicarbonate (standard)
- Sodium Bicarbonate (ultra course)
- Sodium Bicarbonate (50 % fine + 50 % standard)
- Sodium Bicarbonate (50 % fine + 50 % ultra course)
- Sodium Bicarbonate (50 % standard + 50 % ultra course)
- Sodium Bicarbonate (33 % fine + 33 % standard + 33 % ultra course)
- Cellets 500
- Lomma Beach Sand

Granulation and Conditioning

200 g lactose was wet granulated using a mixture of 10 g Polyvidone (PVP) and 40 g water, mixed in a planetary mixer and dried at 40 degrees Celsius.

The water-activity in both non-granulated and granulated lactose was increased using NaCl excitators with 75 % relative humidity (RH) over a period of at least two weeks.

Methods

The powders were studied using the angle of repose and compressibility index methods detailed in the introduction.

Tapped Density and Compressibility Index

Due to budget restraints the compressibility index testing was carried out by hand, though it's worth noting that there exist machines that can do the tapping for you. In this study instead was used regular measuring glass' which can be found in most laboratories as standard equipment. Three different sizes were used, with diameters of 2.5 cm, 3 cm and 3.5 cm respectively. The size of the measuring glass was one of three variables studied, the other two being number of taps and amount of powder. Between each test the powder in question was mixed by hand to make sure there was no lingering compression left over from the previous test.

Angle Of Repose

For the angle of repose testing a special laboratory station was designed, see below for more details. The powders were tested in regards to amount of powder, fixed vs free base, common vs non-common base, and fixed vs adjusted funnel height. The piles of powders were then photographed using a digital camera and the angle then determined on a computer using the software ImageJ.

Angle Of Repose Measuring Station

A special measuring station for the angle of repose experiments were designed and created by Prototyplabbet in Lund, Sweden. The measuring station can be seen in figure 5. It contains a small funnel for the powder to be put in, which also has an easy opening mechanism of a small metal plate near the funnel opening which can quickly be pulled out and initiate powder flow through the opening. The funnel has an adjustable height, as well as a ruler on the side for easy height measurement. The base where the powder will land is a very smooth marble disc, which is mounted on a separate structure, i. e. not connected to the funnel structure, in order to minimize vibrations in the powder pile. The legs on the marble base as well as the funnel structure are all adjustable, in order to create a completely flat working surface, not depending on the benches of the laboratory itself. A spirit level was not built into the structure but used separately, though for those interested in building their own angle of repose measuring station that is a feature which can be added.

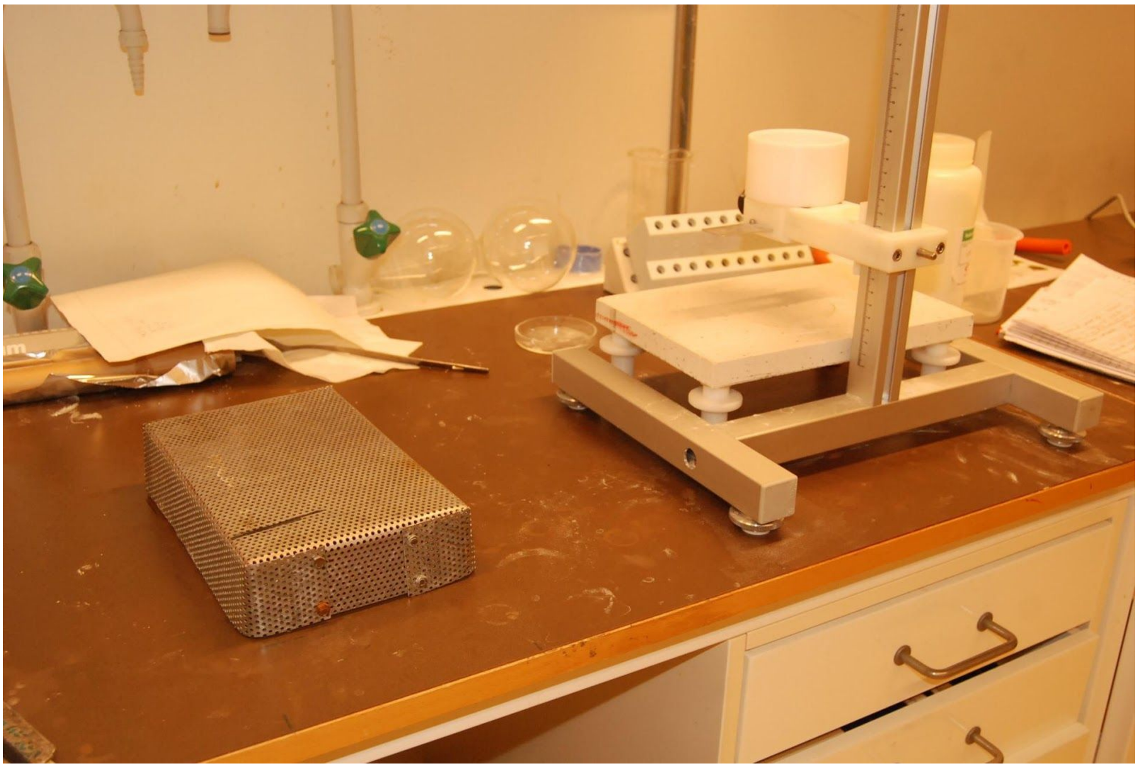

Figure 5 Measuring set-up for the angle of repose tests. On the left the stand for the camera, and on the right the station designed by Prototyplabbet. Photo by Linnea Sternefält.

Comment regarding flow through orifice measurements

The measurement station detailed above, can also be used for flow through orifice experiments, though for the experiments in this report that was not the case. Flow through orifice experiments involve measuring the time it takes for the powder to exit the funnel, and can usually be combined with angle of repose measurements, but was in this case found to be too difficult to do by hand. The powders used had either too good flowability and would thus exit the funnel fast and timing it by hand were nigh impossible with any great accuracy. Or, as in the case with lactose, the powders had too poor flowability and would not actually exit the funnel by themselves, and had to be helped on their way, in which case no time measurements at all could be carried out. Flow through orifice experiments should be studied further and under similar conditions as compressibility index and angle of repose, to create a better overall picture of how the different methods compare in regards to each other.

Results

Table 1 summarizes the results of the tapped density measurements, indicating prevailing trends in the results with changing test parameters.

Table 1 Summary of the tapped density measurements, indicating trends after changes in test parameters.

	Increasing mass 50 taps	**Increasing mass 500 taps**	**Container diameter**	**Increasing number of taps, low powder mass**	**Increasing number of taps, high powder mass**
Lactose	Decreasing HR/CCI	Increasing HR/CCI	Mixed, no trend	Increasing	Increasing
Lactose with higher water activity	Mixed, no trend	Mixed, slight increase	Decreasing	Increasing	Increasing
Lactose granulated	Increasing	Increasing	Increasing	Mixed, slight increase	Increasing
Lactose Granulated with higher water activity	Mixed, no trend	Mixed, slight increase	Decreasing	Mixed, slight increase	Increasing
Sodium Bicarbonate fine	Decreasing	Mixed, no trend	Increasing	Mixed, no trend	Increasing
Sodium Bicarbonate ultra course	Mixed, slight increase	Mixed, slight increase	Increasing	Increasing	Mixed, slight increase
Sodium Bicarbonate standard	Increasing	Increasing	Decreasing	Mixed, no trend	Mixed, slight decrease
Sodium Bicarbonate fine+standard	Increasing	Increasing	Decreasing	Mixed, slight increase	Increasing
Sodium Bicarbonate fine+ultra course	Increasing	Increasing	Increasing	Mixed, no trend	Increasing
Sodium Bicarbonate standard+ultra course	Mixed, slight increase	Mixed, no trend	Decreasing	Increasing	Mixed, no trend
Sodium Bicarbonate fine+standard+ultra course	Mixed, no trend	Increasing	Decreasing	Increasing	Increasing
Cellets	Mixed, decrease	Decreasing	Increasing	Increasing	Mixed, no trend
Lomma Beach Sand	Mixed, slight increase	Mixed, slight increase	Decreasing	Increasing	Mixed, no trend

Figure 6 and 7 highlights the measurements for 500 taps with increasing powder mass, separating lactose and sodium bicarbonate results for clarity. The complete, collected results are presented in the appendices. As can be seen in Figure 6, there is a consistent difference in flowability between regular lactose powder and granulated lactose. Figure 7 showcases the sodium bicarbonate results for 500 taps, with ultra coarse, fine and ultra coarse+fine having the lowest overall Hausner Ratio.

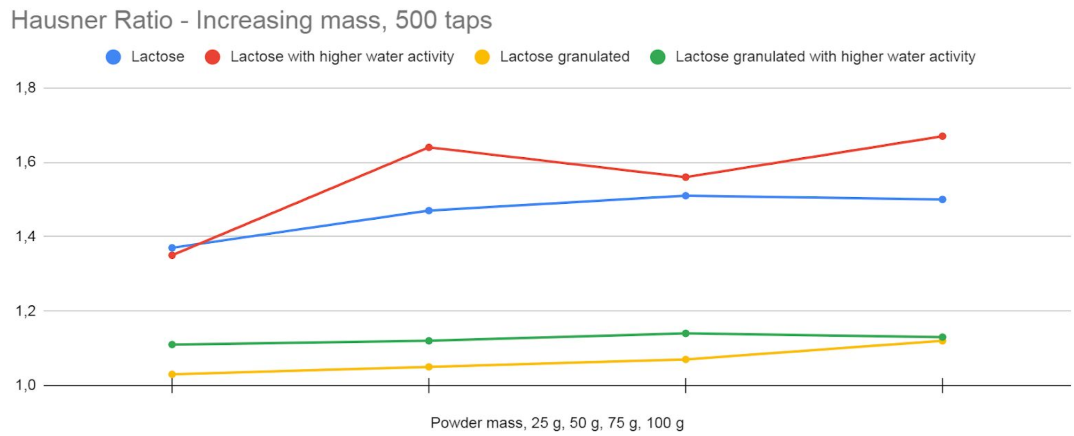

Figure 6 Hausner Ratio results for lactose, 500 taps with increasing powder mass.

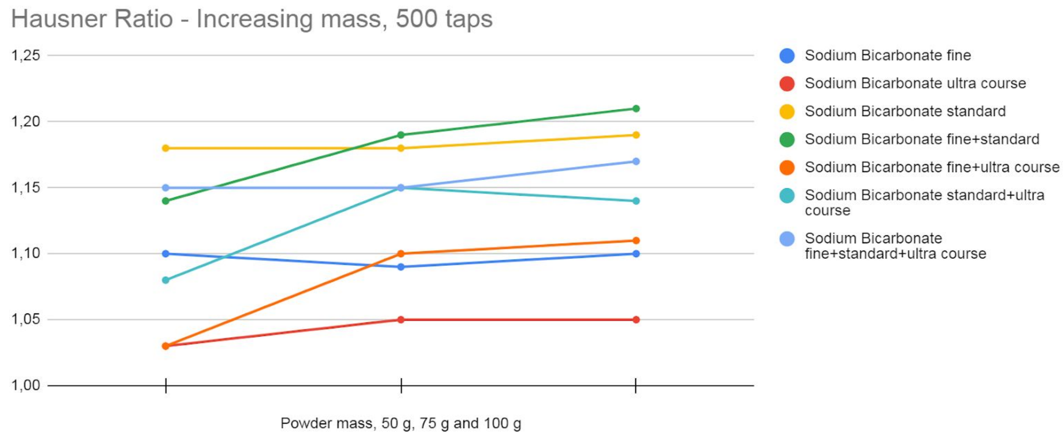

Figure 7 Hausner Ratio results for sodium bicarbonate, 500 taps with increasing powder mass.

Collected results of angle of repose measurements,presented as averages and standard deviations is presented in Table 2, order as listed below. For full data see appendix.

A) Fixed height approximately 3 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

Table 2 Collected results for the angle of repose measurements, presented as averages and standard deviation within parenthesis. Tests A-F are as listed above.

	A	**B**	**C**	**D**	**E**	**F**
Lactose	48 (+/- 2,6)	40(+/- 2,6)	42 (+/- 2,0)	43 (+/- 2,7)	46 (+/- 3,1)	39 (+/- 3,4)
Lactose with Higher Water Activity	47(+/- 1,8)	46(+/- 2,4)	45(+/- 1,7)	47 (+/- 2,2)	52 (+/- 4,5)	48 (+/- 2,6)
Lactose Granulated	35 (+/- 2,3)	37 (+/- 1,9)	36 (+/- 1,7)	36 (+/- 1,4)	37 (+/- 1,1)	34 (+/- 0,9)
Lactose Granulated with Higher Water Activity	36(+/- 1,9)	37(+/- 2,1)	34 (+/- 1,1)	36 (+/- 3,0)	33 (+/- 2,3)	34,(+/- 1,1)
Sodium Bicarbonate fine	29 (+/- 3,8)	30 (+/- 3,4)	21(+/- 4,9)	25 (+/- 3,5)	30 (+/- 2,4)	26 (+/- 2,7)
Sodium Bicarbonate ultra course	25 (+/- 3,1)	23 (+/- 1,3)	26 (+/- 3,6)	26 (+/- 2,1)	23 (+/- 2,0)	25 (+/- 2,5)
Sodium Bicarbonate standard	40 (+/- 3,1)	40(+/- 3,1)	39 (+/- 3,6)	36 (+/- 4,3)	39 (+/- 3,5)	37 (+/- 2,9)
Sodium Bicarbonate fine+standard	30 (+/- 2,5)	32 (+/- 2,7)	29 (+/- 2,2)	31 (+/- 4,9)	32 (+/- 3,2)	30 (+/- 4,5)
Sodium Bicarbonate fine+ultra course	20 (+/- 2,1)	21 (+/- 1,5)	24 (+/- 2,3)	19 (+/- 1,2)	22 (+/- 2,6)	23 (+/- 2,1)
Sodium Bicarbonate standard+ultra course	34 (+/- 2,3)	29 (+/- 4,0)	28 (+/- 1,6)	31 (+/- 3,4)	34 (+/- 3,6)	32 (+/- 3,3)
Sodium Bicarbonate fine+standard+ ultra course	33 (+/- 3,5)	30 (+/- 3,2)	32 (+/- 3,4)	28 (+/- 3,5)	29 (+/- 4,0)	29 (+/- 2,6)
Cellets	30 (+/- 1,5)	26,(+/- 2,1)	29 (+/- 1,3)	23 (+/- 1,2)	26 (+/- 1,3)	30 (+/- 0,5)
Lommasand*	N/A	N/A	N/A	N/A	N/A	N/A

* Unable to carry out experiments; sand got into the equipment and locked up the release mechanism.

Overall, regular lactose powder and lactose powder with a higher water activity had the worst flowability, and cellets had the best flowability, for tapped density measurements. Angle of repose measurements had similar results, but with ultra coarse Sodium Bicarbonate as the best flowing powder.

Discussion

Tapped Density

Lactose and lactose with higher water activity overall have a notably poorer flowability, compared to the other powders. Granulated lactose and granulated lactose with higher water activity have a lower flowability index than regular lactose, due to larger particle sizes. Increased water activity overall results in slightly poorer flowability than the regular powder, both for lactose and granulated lactose, due to the water functioning as an adhesive between the particles. The presence of water does not affect the flowability as much as granulation. The positive effect on flowability due to an increase in particle sizes is supported by the other powders as well. Cellets show excellent flowability for all experiments, except for when tested with increasing number of taps and a lower powder mass, possibly signifying that lower powder masses do not give as reliable a result. For sodium bicarbonate the overall best flowability was achieved by using only the ultra coarse variant, further pointing to larger particle sizes being advantageous. Contradictory to that, using only the standard variant of sodium bicarbonate or mixtures thereof, resulted in the overall poorest flowability for sodium bicarbonate. Sodium bicarbonate fine, as well as the fine and ultra coarse mixture, showed overall good flowability, though not as good as using just ultra coarse. The contradictory result for standard sodium bicarbonate is possibly due to uneven particle size distribution in one or several of the sodium bicarbonate containers, or the standard sodium bicarbonate had possibly taken up extra water prior to use. All the containers were stored the same during the experiments, but all of them had been opened and used by others before, so prior water contamination can't be ruled out. Further studies needed.

The container diameter does not seem to affect the results significantly, so any diameter should work for performing flowability tests. Too large or too small a container do run into the potential problem of not being suitable for the powder volume, such as the powder volume not being large enough to be able to measure in a bigger measuring glass, but the flowability itself does not appear to be greatly affected.

For powders with good or moderate flowability the number of taps do not appear to greatly affect the results, but for those with poor flowability, such as lactose, there is a notable difference. The flowability index for lactose is higher when using a higher number of taps. Overall a higher number of taps is probably to recommend, if possible. Some of the powders, such as cellets, in some cases actually increased in volume after being tapped, indicating it had not been tapped enough times to actually introduce higher packing density. Changes in powder mass show some effect on the results, with lower powder mass measuring a significant lower flowability index. However, for moderate to high powder mass the mass increase does not show a clear change trend for the flowability index, indicating that the changes may not be due to the increasing mass, but rather natural fluctuations or possible effects from air humidity.

Angle of Repose

For angle of repose the study looked for potential differences with changing height, powder mass and base sizes. Overall these changes in testing do not show any clear trends, e.g. a lower powder mass did not uniformly result in an decrease in flowability index, but instead showed a mixed trend for the different powders. Testing with a common base was the most uniform out of the alternatives, with an overall lowering of flowability when compared to a non-common base. A common base is potentially preferential to use, as the surface the powder is spreading out on is not drastically different from the powder itself.

The angle of repose tests otherwise support the results from the tapped density experiments; increased water activity does not seem to have a great effect, while granulation does. Sodium bicarbonate ultra course has the best flowability and sodium bicarbonate standard has the poorest.

Overall

The trend overall all was for powders with good flowability to have mostly uniform, coherent results, even with changing parameters in the experiment itself. Such as for the ultra coarse sodium bicarbonate, which always scored Excellent on the scale from figure 4. While regular lactose for angle of repose measurements on average ranged from Fair to Poor, and for tapped density measurements scored all the way up to Very, Very Poor, when using a high number of taps and high powder mass. Poor flowing powders thus show a greater sensitivity in experiment performance variables, when compared to good flowing powders, and indicate a potential problem in categorizing flowability between measurements when they are not performed uniformly. The flow character scale appears useful as a rough guide to the flowability of a powder, but does not reflect the full, complex image of powder behaviour in different environments and situations. The scale should probably not be too heavily relied upon, especially when dealing with powders scoring Fair and worse.

The results are comparable to other research in the field, which have shown that granulated lactose, while dependent on particle size, commonly scores from Good to Fair [13]. Regular lactose, on the other hand, has been shown to have a wider spread of results, scoring from Fair up to Very Poor [14].

Conclusion

In conclusion, the powders themselves performed mostly as expected, with the exception of standard sodium bicarbonate. The measurements clearly show the importance of granulation when trying to affect the flowability of a powder, and that water activity in the powder will affect the results but not to a great degree.

As for the methods themselves, the results show a dependence on the experimental conditions. The methods appear to work without problems for all container diameter, but with changes in mass and especially with changes in number of taps, the results will vary.

This highlights the problems with measuring powder flowability. While the angle of repose and tapped density will give a rough estimate of the powder flowability and can be useful when comparing powders to each other, there is perhaps too much potential for experimental variations so that the numbers themselves should not be taken as absolute, unless tested rigorously.

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Appendix A

Tapped Density and Compressibility Index

Below are presented relevant calculated values, for the purpose of analysis.

Lactose

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For lactose the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,29 (+/- 0,04)	22,4 (+/- 2,18)
50 g	1,27 (+/- 0,03)	21,1 (+/- 2,05)
75 g	1,24 (+/- 0,01)	19,4 (+/- 0,78)
100 g	1,24 (+/- 0,02)	19,1 (+/- 1,00)

This was repeated for 500 taps.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,37 (+/- 0,09)	26,9 (+/- 4,93)
50 g	1,47 (+/- 0,03)	31,8 (+/- 1,30)
75 g	1,51 (+/- 0,02)	33,6 (+/- 1,05)
100 g	1,50 (+/- 0,03)	33,5 (+/- 1,53)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,38 (+/- 0,05)	27,3 (+/- 2,59)
3 cm	1,40 (+/- 0,06)	28,2 (+/- 2,93)
3,5 cm	1,25 (+/- 0,07)	20,0 (+/- 4,36)

Lastly a variation in number of taps was investigated looking at 25 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 25 g	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25	1,20 (+/- 0,05)	16,9 (+/- 3,54)
50	1,28 (+/- 0,03)	21,5 (+/- 1,54)
100	1,30 (+/- 0,04)	23,3 (+/- 2,17)
500	1,35 (+/- 0,05)	25,6 (+/- 2,56)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25	1,16 (+/- 0,01)	13,7 (+/- 0,60)
50	1,20 (+/- 0,03)	16,4 (+/- 2,41)
100	1,30 (+/- 0,02)	23,3 (+/- 1,33)
500	1,71 (+/- 0,04)	41,6 (+/- 1,35)

Lactose with Higher Water Activity
First part of the testing looks at how compressibility changes with changing mass for the powder in question. For lactose with a higher water activity the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr’s Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25 g	1,21 (+/- 0,05)	17,4 (+/- 3,23)
50 g	1,42 (+/- 0,06)	29,6 (+/- 3,17)
75 g	1,36 (+/- 0,03)	26,6 (+/- 1,80)
100 g	1,37 (+/- 0,01)	27,2 (+/- 0,67)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25 g	1,35 (+/- 0,07)	25,5 (+/- 4,46)
50 g	1,64 (+/- 0,05)	39,0 (+/- 1,89)
75 g	1,56 (+/- 0,02)	35,7 (+/- 0,81)

100 g	1,67 (+/- 0,02)	40,0 (+/- 0,69)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,46 (+/- 0,04)	31,5 (+/- 2,00)
3 cm	1,39 (+/- 0,02)	28,1 (+/- 1,12)
3,5 cm	1,21 (+/- 0,05)	17,4 (+/- 3,23)

Lastly a variation in number of taps was investigated looking at 25 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 25 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,20 (+/- 0,06)	16,3 (+/- 4,43)
50	1,22 (+/- 0,04)	17,8 (+/- 2,31)
100	1,27 (+/- 0,04)	21,0 (+/- 2,64)
500	1,32 (+/- 0,11)	24,0 (+/- 6,31)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,21 (+/- 0,01)	17,0 (+/- 0,91)
50	1,38 (+/- 0,02)	27,5 (+/- 0,85)
100	1,48 (+/- 0,03)	32,4 (+/- 1,20)
500	1,68 (+/- 0,02)	40,3 (+/- 0,59)

Granulated Lactose

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For granulated lactose the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,00 (+/- 0,03)	-0,06 (+/- 2,76)

50 g	1,02 (+/- 0,01)	1,85 (+/- 0,91)
75 g	1,06 (+/- 0,01)	5,65 (+/- 1,07)
100 g	1,10 (+/- 0,02)	9,20 (+/- 1,21)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,03 (+/- 0,02)	2,62 (+/- 2,20)
50 g	1,05 (+/- 0,02)	5,06 (+/- 1,38)
75 g	1,07 (+/- 0,05)	6,17 (+/- 3,82)
100 g	1,12 (+/- 0,02)	10,8 (+/- 1,27)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,03 (+/- 0,02)	2,44 (+/- 1,54)
3 cm	1,03 (+/- 0,02)	3,11 (+/- 1,90)
3,5 cm	1,04 (+/- 0,02)	3,43 (+/- 1,89)

Lastly a variation in number of taps was investigated looking at 25 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 25 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,03 (+/- 0,03)	3,03 (+/- 2,62)
50	1,02 (+/- 0,03)	1,52 (+/- 2,62)
100	1,05 (+/- 0,00)	4,55 (+/- 0,00)
500	1,06 (+/- 0,02)	5,30 (+/- 1,31)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,07 (+/- 0,02)	6,37 (+/- 1,34)

50	1,10 (+/- 0,02)	8,73 (+/- 1,82)
100	1,11 (+/- 0,02)	10,3 (+/- 1,69)
500	1,14 (+/- 0,03)	12,2 (+/- 2,36)

Granulated Lactose with Higher Water Activity

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For granulated lactose with higher water activity the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,10 (+/- 0,02)	9,34 (+/- 1,60)
50 g	1,10 (+/- 0,02)	9,07 (+/- 1,69)
75 g	1,13 (+/- 0,01)	11,2 (+/- 0,54)
100 g	1,09 (+/- 0,01)	7,86 (+/- 0,78)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,11 (+/- 0,01)	9,76 (+/- 1,04)
50 g	1,12 (+/- 0,02)	10,9 (+/- 1,26)
75 g	1,14 (+/- 0,01)	12,6 (+/- 1,05)
100 g	1,13 (+/- 0,01)	11,3 (+/- 0,64)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,13 (+/- 0,02)	11,4 (+/- 1,41)
3 cm	1,11 (+/- 0,01)	10,1 (+/- 1,15)
3,5 cm	1,10 (+/- 0,02)	8,98 (+/- 1,36)

Lastly a variation in number of taps was investigated looking at 25 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 25 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,08 (+/- 0,03)	7,51 (+/- 2,57)
50	1,11 (+/- 0,01)	9,76 (+/- 1,17)
100	1,10 (+/- 0,00)	9,02 (+/- 0,12)
500	1,11 (+/- 0,02)	9,76 (+/- 1,17)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,07 (+/- 0,01)	6,89 (+/- 0,86)
50	1,09 (+/- 0,01)	7,87 (+/- 1,18)
100	1,09 (+/- 0,01)	8,46 (+/-0,63)
500	1,13 (+/- 0,01)	11,2 (+/- 0,95)

Sodium Bicarbonate (Fine)
First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (fine) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,10 (+/- 0,00)	9,09 (+/- 0,00)
75 g	1,06 (+/- 0,01)	5,61 (+/- 1,21)
100 g	1,06 (+/- 0,01)	5,56 (+/- 1,07)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A

50 g	1,10 (+/- 0,03)	8,70 (+/-2,35)
75 g	1,09 (+/- 0,01)	8,48 (+/- 0,82)
100 g	1,10 (+/- 0,01)	8,88 (+/- 1,16)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,04 (+/- 0,15)	1,54 (+/- 18,6)
3 cm	1,09 (+/- 0,03)	8,07 (+/- 2,28)
3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,06 (+/ 0,02)	5,50 (+/- 1,28)
50	1,06 (+/- 0,02)	5,56 (+/- 1,37)
100	1,09 (+/- 0,04)	7,84 (+/- 3,49)
500	1,09 (+/- 0,02)	7,83 (+/- 1,47)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,03 (+/- 0,01)	3,13 (+/- 0,65)
50	1,07 (+/- 0,02)	6,79 (+/- 1,81)
100	1,07 (+/- 0,01)	6,89 (+/- 1,12)
500	1,09 (+/- 0,01)	8,39 (+/- 0,60)

Sodium Bicarbonate (Ultra Coarse)
First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (ultra coarse) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,03 (+/- 0,03)	2,76 (+/- 2,86)
75 g	1,06 (+/- 0,04)	5,28 (+/- 3,60)
100 g	1,05 (+/- 0,02)	4,76 (+/- 1,70)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,03 (+/- 0,02)	2,44 (+/- 1,54)
75 g	1,05 (+/- 0,04)	5,03 (+/- 3,42)
100 g	1,05 (+/- 0,02)	4,42 (+/- 1,68)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,03 (+/- 0,03)	2,69 (+/- 2,79)
3 cm	1,04 (+/-0,00)	4,00 (+/- 0,00)
3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,01 (+/- 0,03)	0,69 (+/- 2,53)
50	1,01 (+/- 0,03)	0,69 (+/- 2,53)
100	1,01 (+/- 0,03)	0,69 (+/- 2,53)
500	1,01 (+/- 0,02)	1,43 (+/- 1,24)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,05 (+/- 0,01)	4,58 (+/- 1,18)
50	1,05 (+/- 0,02)	4,93 (+/- 1,57)
100	1,05 (+/- 0,01)	4,58 (+/- 1,18)
500	1,06 (+/- 0,02)	5,29 (+/- 2,07)

Sodium Bicarbonate (Standard)
First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (standard) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,15 (+/- 0,03)	12,8 (+/- 2,23)
75 g	1,15 (+/- 0,02)	13,1 (+/- 1,35)
100 g	1,18 (+/- 0,02)	15,1 (+/- 1,14)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,18 (+/- 0,03)	15,3 (+/- 2,05)
75 g	1,18 (+/- 0,04)	15,6 (+/- 2,78)
100 g	1,19 (+/- 0,02)	16,2 (+/- 1,08)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,22 (+/- 0,02)	18,2 (+/- 1,31)
3 cm	1,21 (+/- 0,03)	17,3 (+/- 2,11)

3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,14 (+/- 0,04)	12,1 (+/- 3,46)
50	1,20 (+/- 0,05)	16,4 (+/- 3,76)
100	1,22 (+/- 0,04)	18,0 (+/- 2,74)
500	1,18 (+/- 0,00)	14,9 (+/- 0,00)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,21 (+/- 0,01)	17,4 (+/- 0,63)
50	1,20 (+/- 0,01)	16,7 (+/- 0,87)
100	1,20 (+/- 0,04)	16,8 (+/- 2,43)
500	1,20 (+/- 0,02)	16,5 (+/- 1,22)

Sodium Bicarbonate 50 % fine/50 % standard
First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (fine+standard) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,10 (+/- 0,04)	9,26 (+/- 3,17)
75 g	1,16 (+/- 0,03)	14,1 (+/- 1,96)
100 g	1,18 (+/- 0,01)	15,3 (+/- 1,04)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)

25 g	N/A	N/A
50 g	1,14 (+/- 0,02)	11,9 (+/- 1,76)
75 g	1,19 (+/-0,02)	16,0 (+/- 1,58)
100 g	1,21 (+/- 0,02)	17,6 (+/- 1,10)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,18 (+/- 0,05)	15,0 (+/- 3,88)
3 cm	1,17 (+/- 0,04)	14,1 (+/- 3,20)
3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,10 (+/- 0,05)	8,84 (+/- 3,64)
50	1,09 (+/- 0,05)	8,08 (+/- 4,42)
100	1,11 (+/- 0,04)	9,60 (+/- 3,22)
500	1,13 (+/- 0,03)	11,1 (+/- 1,98)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,17 (+/- 0,01)	14,7 (+/- 1,05)
50	1,17 (+/- 0,01)	14,7 (+/- 1,05)
100	1,21 (+/- 0,02)	17,3 (+/- 1,40)
500	1,21 (+/- 0,02)	17,6 (+/- 1,65)

Sodium Bicarbonate 50 % fine/ 50 % ultra coarse

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (fine + ultra coarse) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,03 (+/- 0,02)	2,42 (+/- 1,51)
75 g	1,01 (+/- 0,04)	7,16 (+/- 3,23)
100 g	1,11 (+/- 0,02)	9,58 (+/- 1,27)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,03 (+/- 0,01)	3,24 (+/- 1,22)
75 g	1,10 (+/- 0,02)	9,03 (+/- 1,83)
100 g	1,11 (+/- 0,01)	10,2 (+/- 0,59)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,04 (+/- 0,01)	3,96 (+/- 1,20)
3 cm	1,05 (+/- 0,03)	5,05 (+/- 2,64)
3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,02 (+/- 0,01)	1,63 (+/- 1,41)
50	1,02 (+/- 0,01)	1,63 (+/- 1,41)
100	1,03 (+/- 0,02)	3,27 (+/- 1,39)
500	1,03 (+/- 0,00)	2,46 (+/- 0,04)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25	1,10 (+/- 0,02)	8,73 (+/- 1,82)
50	1,12 (+/- 0,01)	10,3 (+/- 0,69)
100	1,12 (+/- 0,00)	10,7 (+/- 0,00)
500	1,12 (+/- 0,00)	10,7 (+/- 0,00)

Sodium Bicarbonate 50 % standard/50 % ultra coarse

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (standard+ultra coarse) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr’s Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,07 (+/- 0,03)	6,09 (+/- 2,46)
75 g	1,13 (+/- 0,03)	11,7 (+/- 2,35)
100 g	1,13 (+/- 0,02)	11,0 (+/- 1,84)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,08 (+/- 0,02)	7,32 (+/- 2,08)
75 g	1,15 (+/- 0,03)	13,4 (+/- 1,89)
100 g	1,14 (+/- 0,02)	12,3 (+/- 1,84)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr’s Compressibility Index (Standard Deviation)
2,5 cm	1,16 (+/- 0,03)	14,0 (+/- 2,52)
3 cm	1,13 (+/- 0,03)	11,1 (+/- 1,94)

3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,08 (+/- 0,03)	7,24 (+/- 2,32)
50	1,08 (+/- 0,03)	7,24 (+/-2,32)
100	1,09 (+/- 0,02)	8,05 (+/- 1,27)
500	1,10 (+/- 0,02)	8,87 (+/- 1,35)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,11 (+/- 0,00)	10,0 (+/- 0,00)
50	1,14 (+/- 0,01)	12,1 (+/- 0,72)
100	1,14 (+/- 0,01)	12,1 (+/- 0,72)
500	1,13 (+/- 0,02)	11,3 (+/- 1,25)

Sodium Bicarbonate 33 % fine/33 % standard/33 % ultra coarse
First part of the testing looks at how compressibility changes with changing mass for the powder in question. For sodium bicarbonate (fine+standard+ultra coarse) the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,13 (+/- 0,03)	11,7 (+/- 2,05)
75 g	1,11 (+/- 0,03)	9,97 (+/- 2,41)
100 g	1,13 (+/- 0,02)	11,4 (+/- 1,16)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,15 (+/- 0,03)	12,9 (+/- 2,16)
75 g	1,15 (+/- 0,01)	12,9 (+/- 1,05)
100 g	1,17 (+/- 0,01)	14,4 (+/- 0,46)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diamater	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	1,14 (+/- 0,02)	12,1 (+/- 1,81)
3 cm	1,09 (+/- 0,03)	8,60 (+/- 2,13)
3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,10 (+/- 0,05)	9,04 (+/- 3,81)
50	1,14 (+/- 0,04)	12,1 (+/- 3,19)
100	1,15 (+/- 0,04)	12,8 (+/- 3,2)
500	1,16 (+/- 0,03)	13,6 (+/- 1,96)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,11 (+/- 0,01)	10,2 (+/- 0,68)
50	1,14 (+/- 0,01)	12,2 (+/- 0,68)
100	1,15 (+/- 0,02)	12,9 (+/- 1,18)
500	1,17 (+/- 0,01)	14,5 (+/- 0,68)

Cellets

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For cellets the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,07 (+/- 0,02)	6,86 (+/- 2,03)
50 g	1,00 (+/- 0,02)	-0,32 (+/- 1,76)
75 g	1,00 (+/- 0,01)	-0,58 (+/- 0,98)
100 g	1,02 (+/- 0,02)	1,54 (+/- 1,43)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	1,09 (+/- 0,03)	8,61 (+/- 2,59)
50 g	1,03 (+/- 0,02)	2,93 (+/- 1,81)
75 g	1,02 (+/- 0,01)	1,68 (+/- 1,35)
100 g	1,02 (+/- 0,00)	1,82 (+/- 0,33)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diamater	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
2,5 cm	0,98 (+/- 0,02)	-1,74 (+/- 1,91)
3 cm	0,99 (+/- 0,02)	-1,15 (+/- 1,78)
3,5 cm	1,05 (+/- 0,02)	5,08 (+/- 1,74)

Lastly a variation in number of taps was investigated looking at 25 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 25 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,02 (+/- 0,02)	2,34 (+/- 2,03)
50	1,05 (+/- 0,04)	4,60 (+/- 3,98)
100	1,05 (+/- 0,02)	4,48 (+/- 1,89)

500	1,10 (+/- 0,02)	8,97 (+/- 1,79)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,01 (+/- 0,01)	1,12 (+/- 0,47)
50	1,01 (+/- 0,01)	1,40 (+/- 0,95)
100	1,00 (+/- 0,02)	0,27 (+/- 1,75)
500	1,03 (+/- 0,02)	2,52 (+/- 1,43)

Lomma Sand

First part of the testing looks at how compressibility changes with changing mass for the powder in question. For the Lomma sand the number of taps was fixed to 50, diameter of the measuring glass was 3.5 cm and the mass was measured at 25 g, 50 g, 75 g and 100 g. Average calculated values for Hausner Ratio and Carr's Compressibility Index are shown in the table below.

Mass	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,04 (+/- 0,02)	3,53 (+/- 2,28)
75 g	1,03 (+/- 0,01)	3,33 (+/- 1,03)
100 g	1,06 (+/- 0,02)	5,70 (+/- 1,72)

This was repeated for 500 taps.

Mass at 500 taps	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25 g	N/A	N/A
50 g	1,05 (+/- 0,02)	4,56 (+/- 1,64)
75 g	1,04 (+/- 0,00)	4,00 (+/- 0,00)
100 g	1,07 (+/- 0,01)	6,45 (+/- 1,16)

Third part consisted of looking at a change in measuring glass diameter, from 2,5 cm to 3 cm and 3,5 cm, with a fixed number of taps at 50 and a fixed mass at 25 g. Average calculated values below.

Diameter	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)

2,5 cm	1,09 (+/- 0,01)	8,02 (+/- 1,13)
3 cm	1,05 (+/- 0,02)	4,90 (+/- 1,52)
3,5 cm	N/A	N/A

Lastly a variation in number of taps was investigated looking at 50 g and 100 g powder mass, at a glass diameter of 3,5 cm with number of taps at 25, 50, 100 and 500. See below.

Number of taps for 50 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,02 (+/- 0,02)	2,02 (+/- 1,75)
50	1,02 (+/- 0,02)	2,02 (+/-1,75)
100	1,03 (+/- 0,00)	3,06 (+/- 0,05)
500	1,05 (+/- 0,02)	5,08 (+/- 1,70)

Number of taps for 100 g	Average Hausner Ratio (Standard Deviation)	Average Carr's Compressibility Index (Standard Deviation)
25	1,06 (+/- 0,00)	5,94 (+/- 0,05)
50	1,07 (+/- 0,01)	6,93 (+/- 0,83)
100	1,08 (+/- 0,00)	7,43 (+/- 0,63)
500	1,08 (+/- 0,02)	6,92 (+/- 1,65)

Appendix B

Angle of Repose

Granulated Lactose with Higher Water Activity

A) Fixed height approximately 3 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common base
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	33.0	39.0	35.8	32.7	34.4	34.1
#2	36.1	39.3	34.6	40.3	33.4	33.3
#3	35.6	35.7	32.3	35.3	33.7	33.6
#4	38.5	36.6	34.0	33.9	36.2	32.8
#5	35.2	34.0	34.0	34.4	29.7	35.2
#6	37.2	38.5	34.4	38.9	31.3	35.6

Sodium Bicarbonate Standard

A) Fixed height approximately 3 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	42.5	39.6	33.9	30.1	37.5	33.6
#2	39.4	41.1	41.4	31.3	39.8	35.7
#3	38.4	40.1	34.6	39.4	44.7	35.0

#4	39.4	34.0	39.0	36.4	40.1	36.2
#5	35.4	43.4	40.8	40.3	34.0	37.8
#6	44.0	40.1	42.3	38.0	39.3	42.0

Lactose with Higher Water Activity

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	45.4	44.7	46.6	46.8	54.8	49.8
#2	45.6	47.8	45.0	48.3	53.3	49.1
#3	44.6	47.1	41.6	47.5	46.7	47.3
#4	47.8	48.3	44.1	43.1	54.9	45.2
#5	49.0	45.3	45.0	49.2	47.4	44.5
#6	48.1	42.0	45.4	45.7	46.8	50.8

Lommasand

Sand gets stuck in the equipment, stopping the opening mechanism from working properly. Unable to do measurements.

Granulated Lactose

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	33.7	36.1	37.4	36.9	38.6	33.7
#2	31.0	36.9	36.6	37.9	36.6	32.4
#3	37.3	35.2	35.0	36.6	37.4	33.2
#4	35.5	38.6	36.8	35.8	37.8	34.8
#5	36.6	36.6	32.9	33.8	36.5	33.4
#6	35.6	40.5	36.4	35.7	35.5	34.3

Lactose

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	50.3	40.0	43.5	39.8	41.6	33.8
#2	46.4	35.5	41.3	39.9	47.6	39.6
#3	50.6	37.8	39.7	41.9	48.1	35.8
#4	47.3	41.9	45.0	44.5	42.6	37.4
#5	43.8	42.1	41.5	45.5	47.8	41.4
#6	48.3	40.5	40.7	45.8	48.6	42.8

Cellets

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	27.3	25.9	29.2	21.7	26.0	28.9
#2	31.4	24.4	28.5	21.9	27.7	30.4
#3	31.2	25.1	30.0	23.0	25.3	29.8
#4	29.5	30.4	28.3	23.4	24.6	29.6
#5	29.0	25.5	29.7	24.8	24.1	29.3
#6	29.5	26.8	26.5	24.0	26.4	29.1

Sodium Bicarbonate (fine)

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	25.6	31.7	13.1	21.4	31.0	27.5
#2	26.2	28.4	22.5	26.2	30.0	30.2
#3	28.1	30.2	20.7	31.4	31.6	22.4
#4	33.6	35.5	26.3	22.7	32.5	24.6
#5	28.1	30.0	24.9	24.0	29.0	25.9
#6	34.5	25.2	17.9	24.0	25.9	27.8

Sodium Bicarbonate (33 % standard + 33 % fine + 33 % ultra course)

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base

E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	30.2	30.2	27.2	28.9	36.4	28.9
#2	28.6	35.0	36.5	28.3	30.2	25.5
#3	35.6	30.6	34.2	27.0	30.3	30.1
#4	37.2	26.0	30.3	33.1	25.1	31.7
#5	36.3	26.9	33.4	27.0	26.1	32.1
#6	32.1	29.0	29.6	22.3	28.3	27.4

Sodium Bicarbonate (50 % standard + 50 % ultra course)

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	32.8	29.0	28.2	27.6	35.1	33.8
#2	34.9	31.4	28.9	35.8	28.4	37.5
#3	30.1	29.4	26.6	33.9	33.8	30.6
#4	33.9	31.6	28.6	29.2	39.6	28.1
#5	34.6	27.8	25.4	27.5	34.6	30.8
#6	36.8	32.8	29.9	29.9	34.8	31.0

Sodium Bicarbonate (50 % fine + 50 % ultra course)

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base

B) Adjusted height with an attempted, continous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	20.1	22.0	22.8	19.1	24.7	24.3
#2	23.5	22.7	20.1	18.1	21.5	21.1
#3	21.3	20.7	25.8	19.0	20.5	23.0
#4	17.2	20.1	25.2	19.4	17.5	24.3
#5	19.9	19.6	23.1	16.7	21.3	25.7
#6	20.1	18.9	26.1	20.3	23.8	20.3

Sodium Bicarbonate (50 % fine + 50 % standard)

A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	27.1	35.8	26.9	34.2	32.7	23.1
#2	30.6	30.1	26.4	31.8	33.1	30.2
#3	29.9	30.8	31.4	27.4	35.9	33.0
#4	28.1	29.7	31.0	23.8	31.5	28.4
#5	33.4	30.5	31.0	37.0	28.2	36.6
#6	33.0	34.9	29.6	34.0	27.6	29.8

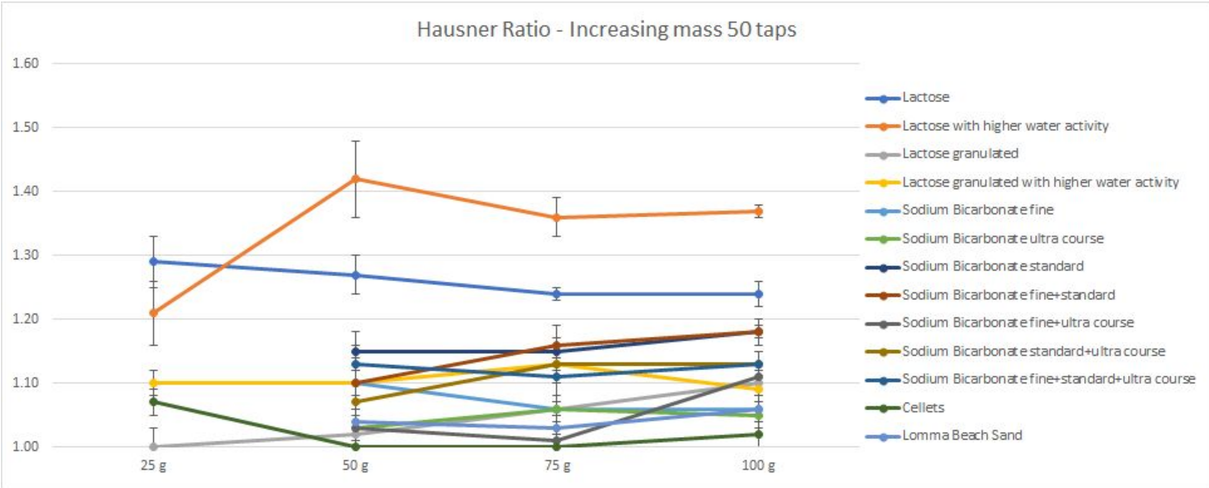
Sodium Bicarbonate (Ultra Course)

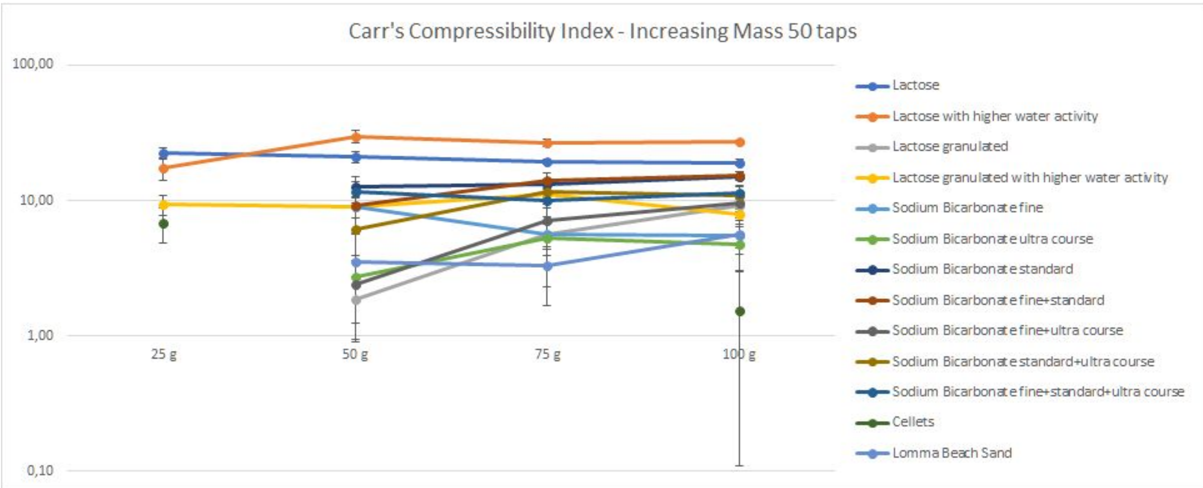
A) Fixed height approximately 2 cm above expected pile height, 50 g, fix base with diamater 11 cm, non-common base
B) Adjusted height with an attempted, continuous height of 2 cm above the top of the pile, 50 g, fix base diameter 11 cm, non-common height
C) Fixed height, 25 g, fix base diameter 11 cm, non-common base
D) Fixed height, 50 g, open base, non-common base
E) Fixed height, 50 g, fix base diameter 8 cm, non-common base
F) Fixed height, 50 g, fix base diameter 11 cm, common base

	A	B	C	D	E	F
#1	23.3	23.3	28.9	28.9	24.0	23.7
#2	22.3	22.1	25.9	26.9	21.9	26.2
#3	28.7	23.9	20.1	23.5	19.6	20.3
#4	22.0	25.6	22.6	24.4	23.9	25.1
#5	29.0	22.9	26.3	23.9	23.9	26.2
#6	25.1	22.3	29.5	25.7	24.9	27.1

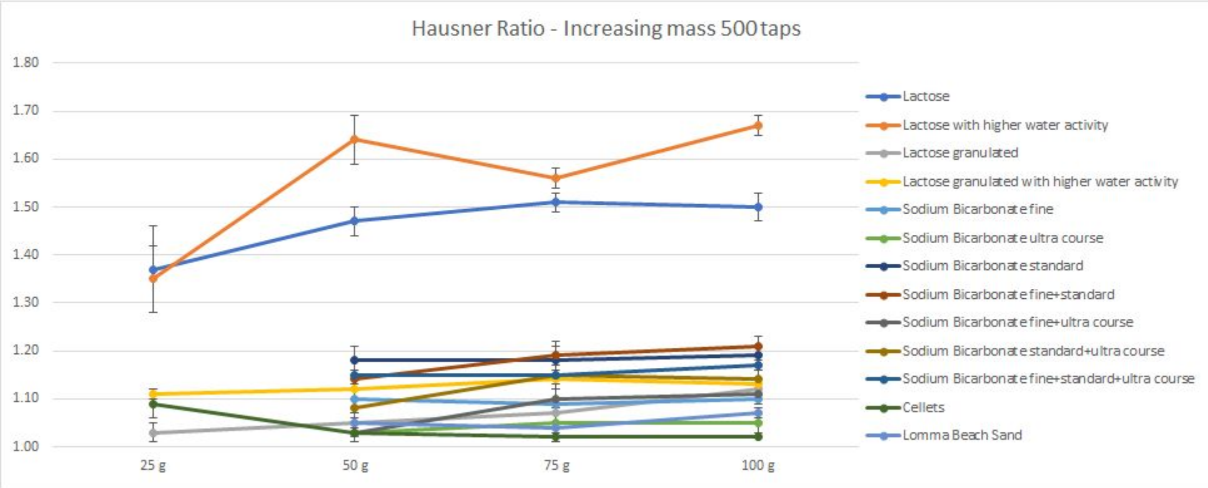
Appendix C

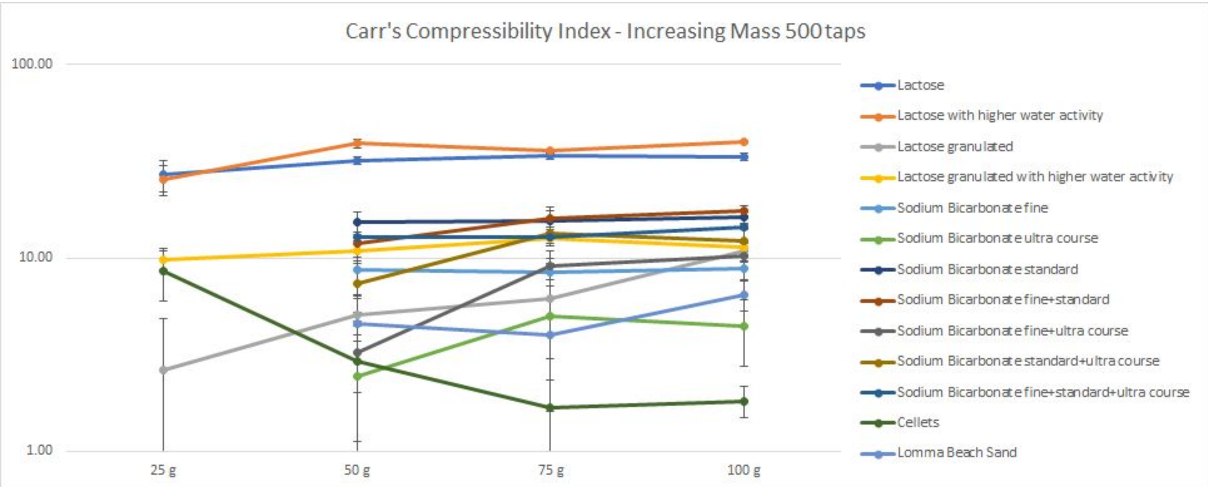
Collected results for tapped density measurements, with fixed 50 taps and increasing powder mass, for Hausner's Ratio and Carr's Compressibility Index with semilog-scale:



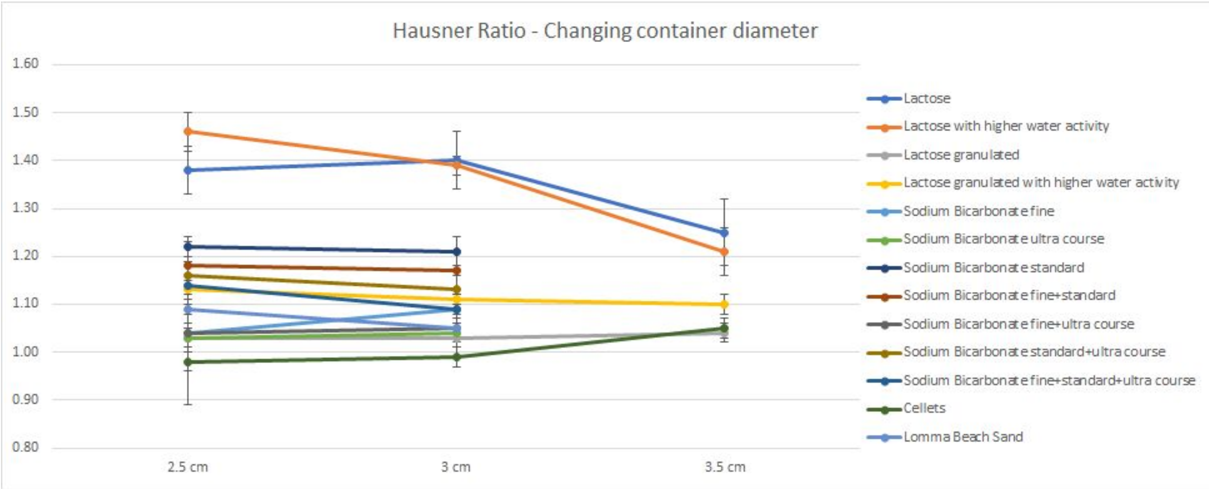


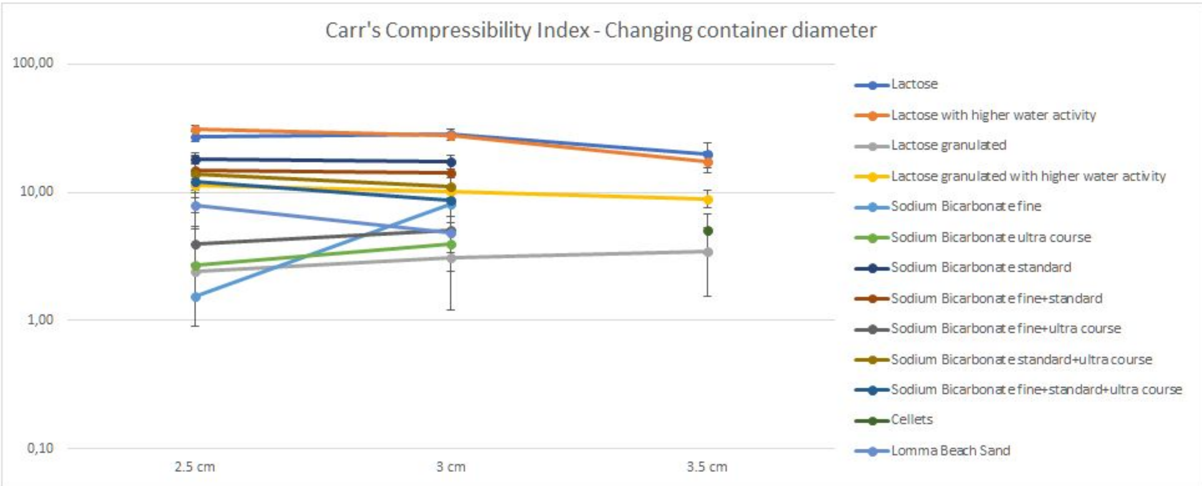
Collected results for tapped density measurements, with fixed 500 taps and increasing powder mass, for Hausner's Ratio and Carr's Compressibility Index with semilog-scale:



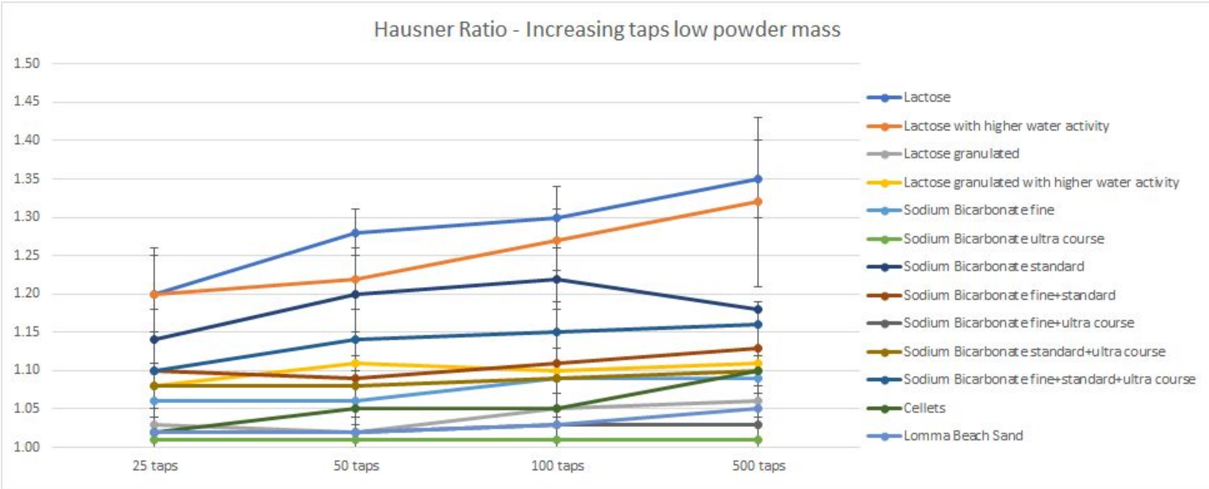


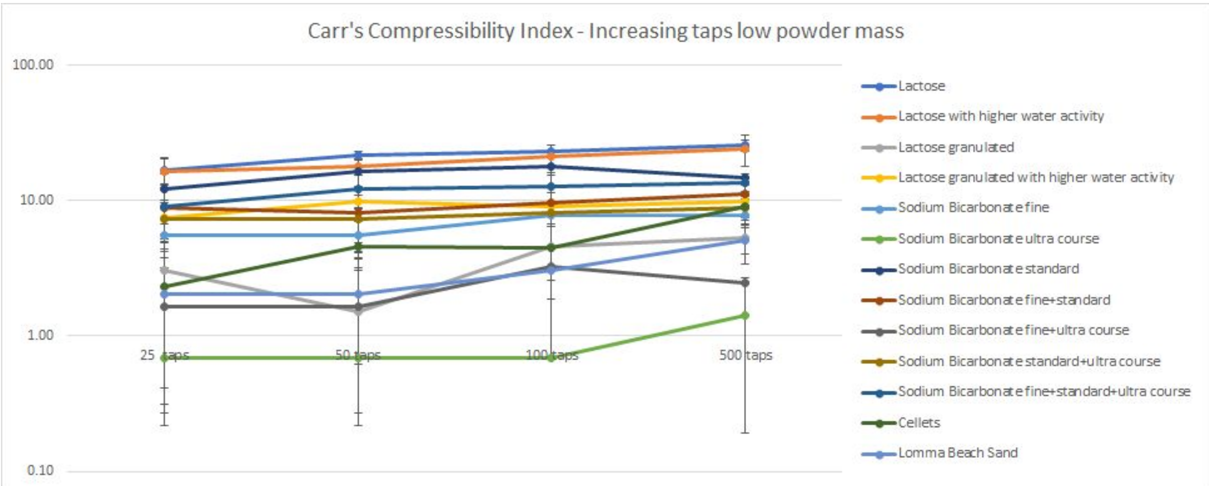
Collected results for tapped density measurements, with fixed powder mass and changing container diameter, for Hausner's Ratio and Carr's Compressibility Index with semilog-scale:





Collected results for tapped density measurements, with fixed, low powder mass and increasing number of taps, for Hausner's Ratio and Carr's Compressibility Index with semilog-scale:





Collected results for tapped density measurements, with fixed, high powder mass and increasing number of taps, for Hausner's Ratio and Carr's Compressibility Index with semilog-scale: