A Method to Analyze Shear Cell Data of Powders Measured under Different Initial Consolidation Stresses

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Abstract

Purpose: The shear cell test has been widely used to characterize flow properties of powders and granular materials. The purpose of this study is to address the gap between the extensive usage of the test and the limited methods available to analyze the data, and to introduce methodologies for comparing results for different initial consolidation stresses, materials, and testing devices. **Method:** A library of shear cell data was established. Forty-one powders were included, and each material was tested under four different initial consolidation stresses. For each initial consolidation stress, 3 sampling replicates were performed. **Results:** A dimensionless cohesion, C^* , was defined as the cohesion divided by the initial consolidation stress. By identifying a correlation between the flow function coefficient (ffc) and C^* , the effects of the initial consolidation stress and the testing device were separated. In addition, by identifying a mathematical correlation between the unconfined yield strength and the cohesion, the yield loci from different initial consolidation stresses could be collapsed into a single material characteristic line, enabling one to characterize each material by a single number (the characteristic slope). This approach can be used to economically compare different materials, or different testing devices. **Conclusion:** The proposed method augments shear cell data analysis and significantly reduces the complexity of the shear cell data.

Key words: Powder flow, Shear cell, Mohr circle, Database

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I. Introduction

Powders and granular materials are commonly handled and processed in a wide range of industries.[1] In the pharmaceutical industry, active pharmaceutical ingredients are mixed with excipient materials and processed through a series of powder-based unit operations (e.g, granulation, drying, milling, and compaction) in order to produce the final drug product.[2, 3] Similar powder processing is also widely practiced for cosmetic, catalyst, chemical, petrochemical and food products.[4-7]

Powder flow behavior, one of the most critical properties of powders and granular materials, can change significantly during various stages of processing,[8] and if the change is poorly understood, monitored, or controlled, process performance and product quality can be adversely affected.[9] Therefore, the ability to understand, measure, and predict powder flow at each process unit is vital to ensure controllable processes and reproducible products.[10] Ideally, this capability can be achieved by studying rigorously the flow of different materials in various types of process equipment. However, this can be complex and challenging because powder flowability, by definition, results from a combination of inherent material properties, environmental and process factors, and even choice of characterization method.[11-13]

In industrial practice, in order to predict the flow of a material in a given piece of equipment, or to compare the flow of a new material to an existing material, a practical way is to implement a standardized lab scale test to measure powder properties.[14] As a result, many characterization techniques have been developed,[15] and efforts have been made to correlate and compare the results obtained in different measurement devices.[16-20]

The shear cell methodology, which was originally developed by A. W. Jenike for design of hoppers and silos,[21] is one of the most common powder flow characterization techniques. It

has been an engineering practice to classify and rank the flowability of different materials according to the extracted flow function coefficient (ffc).[22] The cohesion, the unconfined yield strength, the angle of internal friction, and other design parameters can be extracted from Mohr circle analysis.[23] The methodology has been widely applied for powder characterization, and the testing procedure has been detailed and documented as international standards.[24, 25] The shear cell test has thus been used extensively to characterize the flow properties of powders, and the effect of consolidation state on the powder flow properties has been examined.[26, 27] The effects of particle size, particle shape and the environmental factors, such as storage time, humidity and temperature, have been studied.[28-30] A recent study compared three commercially available shear cells in terms of powder flow properties.[31] In addition, multivariate analysis has been applied to analyze shear cell data along with other flow indices. For example, principal component analysis was used to develop a method for early pharmaceutical formulation development.[32] A partial least square regression model was established to predict powder flowability based on particle size and shape distribution.[33]

While a number of studies have focused on simulating the testing dynamics, examining the effects of various factors on the results, and correlating shear cell data with other characterization techniques, there are very few published studies that have developed methodologies to reduce the complexity of the shear cell data. Specifically, since the measurement is dependent on the initial consolidation stress,[34] a material is usually characterized under different levels of initial consolidation stress in order to generate a family of curves from which parameters can be extracted. It is also quite common to develop a material library of the flow properties of various powder materials, which leads to a multi-dimensional database which can be difficult to interpret. In addition, comparing data measured from different shear cells is, in some cases, also needed.

As the dimensionality of a shear cell database grows, challenges that inevitably need to be addressed are: 1) Correlating different flow parameters to reduce the complexity of the database. 2) Comparing different materials measured under different initial consolidation stresses. 3) Comparing and transferring the database between different types of shear cells.

The purpose of this paper is to introduce such an analysis framework to address the above scenarios. The methodologies are demonstrated using an established shear cell database, which contains 9 catalyst support materials and 32 pharmaceutical materials measured under four different initial consolidation stresses. The remainder of this article is organized as follows: section II describes the materials in the database, the procedure for the shear cell test and the Mohr circle analysis used to extract the flow parameters; section III presents a correlation between different flow parameters, and methods to analyze the shear cell data for different materials, initial consolidation stresses, and testing devices; and finally, section IV is devoted to conclusions.

II. Materials and Methods

The materials used in this study are listed in Tables 1 and 2. Particle size information and conditioned bulk density of the materials are listed in Table 3. The particle size of the materials was determined using a laser-diffraction (LS-13320) analyzer with a Tornado Dry Powder System (Beckmann-Coulter, Brea, California, US). Conditioned bulk density was measured after the standard conditioning cycle of the shear cell test, which is further detailed below.

Shear cell methodology

The flow properties of all blends were characterized using a rotational shear cell supplied as a component of the FT4 Powder Rheometer (Freeman Technology Inc., Worcestershire, UK),

which is shown in figure 1. The testing procedure consisted of four steps: conditioning, consolidation, preshearing, and shearing. The powder was first filled into a glass cylinder. During conditioning, a helical blade moved downwards, and then moved upwards to erase powder history and ensure a homogeneous reproducible state. In consolidation, a vented piston applied the initial consolidation stress (I) to the powder. The powder was then sheared to achieve a steady-state. The shear stress and normal stress were recorded and were indicated as a preshear point. After the preshear point was achieved, the normal stress was lowered and the sample was further sheared to obtain a yield point. The paired preshear-shear procedure was repeated 5 times in total at different normal stresses to obtain a yield locus.[24] Each test generated one preshear point and five yield points.

The shear stress was plotted in terms of the normal stress, which is also known as τ - σ diagram. While models to take into account of shape of the yield locus have been developed,[35] a commonly used approach is the Mohr-Coulomb model to generate a linearized yield locus. A schematic illustration of Mohr circle analysis for a yield locus is shown in Figure 2. A linear regression was fitted through the yield points to obtain a mathematical expression for the linearized yield locus. The intercept of the yield locus on the shear stress τ -axis is defined as the cohesion (τ_1), which can be interpreted as the shear stress required to deform the powder when no normal stress is applied. The slope of the linearized yield locus is $\tan(\varphi)$, where (φ) is the called the angle of internal friction (see Fig. 2), which is a measure of ease with which the powder particles will slide past one another.[36] To extract other flow indices, a Mohr circle was then plotted passing through origin and tangent to the yield locus. The intercept of this Mohr circle with the normal stress σ -axis is defined as the unconfined yield strength (σ_c). A second Mohr circle was drawn tangent to yield locus and passing through the preshear point (σ_p, τ_p),

with its intercept on the σ -normal stress axis called the major principal stress (σ_1). The flow function coefficient (ffc), which is often correlated to the arching phenomenon in hoppers, is defined as the ratio between the major principal stress (σ_1) and the unconfined yield strength (σ_c):[37]

$$ffc = \sigma_1 / \sigma_c \quad (1)$$

While these parameters are typically calculated and reported as independent measurements, they can, in fact, be calculated from the mathematical expression in the Mohr circle analysis. The Mohr-Coulomb model in the τ - σ diagram can be described as:

$$\tau = \sigma * \tan\varphi + \tau_1 \quad (2)$$

For a straight line with slope equal to $\tan(\varphi)$ and intercept (cohesion) τ_1 , the unconfined yield strength can be expressed as a function of the cohesion and the angle of internal friction:

$$\sigma_c = \tau_1 * 2 * \tan(45 + \varphi/2) \quad (3)$$

For a circle tangent to the yield locus and passing through the preshear point (σ_p, τ_p), with its intercept on the σ -axis equal to the major principal stress (σ_1), one can show that the major principal stress can be related to the cohesion, the angle of internal friction, and the coordinate of the preshear point (σ_p, τ_p):

$$\sigma_1 = (1 + \sin \varphi) \left(\left(A - \sqrt{A^2 \sin^2 \varphi - \tau_p^2 \cos^2 \varphi} \right) / \cos^2 \varphi \right) - \tau_1 / \tan \varphi \quad (4)$$

where $A = \sigma_p + \tau_1 / \tan \varphi$

In this study, the normal stresses during the shear cell test, and Mohr-Coulomb model to extract flow properties were selected as are typical for material characterization purposes.[38] The four levels of initial consolidation stresses were 3 kPa, 6 kPa, 9 kPa, and 15 kPa for all materials studied. At the initial consolidation stress of 3kPa, the shear stresses to achieve incipient flow were obtained at normal stresses of 2 kPa, 1.75 kPa, 1.5 kPa, 1.25 kPa, and 1 kPa. Similarly, at the initial consolidation of 6 kPa, shear stresses under normal stresses of 4 kPa, 3.5 kPa, 3 kPa, 2.5 kPa, and 2 kPa were recorded. At the initial consolidation stress of 9 kPa, shear stresses under normal stresses of 7 kPa, 6 kPa, 5 kPa, 4 kPa, and 3kPa were obtained. For the initial consolidation stress of 15kPa, shear stresses at normal stresses of 9 kPa, 8 kPa, 7 kPa, 6 kPa, and 5 kPa were recorded. Before obtaining each yield point, the materials reached a steady-state flow at the pre-defined preshear consolidation stress. Sampling replicates of 3 shear stresses were conducted at each normal stress.

III. Results and discussion

Correlation between the flow function coefficient and the cohesion

The materials in the database covered a wide range of flow behavior. Figure 3 examines the correlation between the flow function coefficient and the cohesion (kPa) for all the 41 materials at the same initial consolidation stress, and shows that the two parameters have an intrinsic inverse correlation (power law with exponent of -1). The inverse correlation at all the initial consolidation stresses is statistically significant ($p < 0.05$). The inverse correlation between the flow function coefficient and the cohesion is consistent with a previous study on solid mixtures.[39] Importantly, the pre-factor coefficient of the power correlation is a material-independent characteristic, and only depends on the initial consolidation stress. Moreover, as

shown in Figure 4, the pre-factor coefficient is linearly proportional to the the initial consolidation stress (Adjusted R-squared = 0.996, $p < 0.05$).

The flow function coefficient, which, by definition, is obtained from the intercepts of the two Mohr circles, can also be calculated through its correlation with the cohesion. To further investigate this correlation, a dimensionless cohesion, C^* , was defined as:

$$C^* = \tau_1 \text{ (kPa)} / I \text{ (kPa)} \quad (5)$$

where I is the initial consolidation stress. As shown in figure 5, the flow function coefficient for all materials, for all values of the initial consolidation stress collapse to a single curve when plotted as a function of the dimensionless cohesion C^* , once again exhibiting inverse proportionality. The correlation between them is statistically significant (adjusted R-squared = 0.979, $p < 0.05$). The correlation can be described as:

$$ffc = E / C^* \quad (6)$$

where E is a constant. Based on the usual interpretation of the flow function, materials can now be classified based on the dimensionless cohesion, C^* :

$C^* \leq 0.048$, free-flowing

$0.048 < C^* \leq 0.121$, easy-flowing

$0.121 < C^* \leq 0.242$, cohesive

$C^* > 0.242$, very cohesive or not flowing

The distinction between very cohesive materials and non-flowing materials has not been made in this study because materials with C^* higher than 0.484 were not tested. The advantage

of this classification is that while the criteria based on the flow function coefficient does not take into account the initial consolidation stress, calculation of C^* by definition includes the effect of the initial consolidation stress.

The proportionality constant $E = 0.485$ in the figure 5 is independent of both material characteristics and the initial consolidation stress, but it depends on geometric factors of the testing device during consolidation, and can be used as an equipment characteristic (or to compare measurements obtained in different devices). By means of a simple logarithmic transformation, the correlation between the flow function coefficient and the dimensionless cohesion C^* can be linearized, as shown in figure 6.

Combining the experimental results with the mathematical relation introduced in section II, the constant E can be used to describe another material property:

$$\sigma_1/I = 2 * E * \tan(45^\circ + \varphi/2) \quad (7)$$

where σ_1 is the major principal stress, which is the relative consolidation state when the material is in steady-state flow under the preshear normal stress; φ is the angle of internal friction, and the plane $(45^\circ + \varphi/2)$ to the major principal stress is the direction where the shear band with lowest deformation resistance is most likely to occur.[40] Therefore, the change of the major principal stress is related to the equipment characteristic, E , and the material property, φ . This is consistent with the previous studies. It has been observed that when powder reaches a steady-state, the consolidation state is a material property, and only depends on the applied stress.[41] In addition, previous researchers showed that the impeller torque, which is related to the shear stress, increased linearly with the fill level or applied normal stress.[42, 43]

Correlation between the unconfined yield strength and the cohesion

As described in section II, the ratio between σ_c , the unconfined yield strength (UYS) and the cohesion is only dependent on the angle of internal friction. Experimental results in this study show that the unconfined yield strength (σ_c) is linearly correlated with the cohesion. Figure 7(a) shows the yield loci of maize starch measured under four initial consolidation stresses. As shown in figure 7(b), by plotting the UYS as a function of the cohesion, all the yield points at different initial consolidation stresses can be described by a single line passing through the origin. In other words, as the initial consolidation stress changes, the ratio between the change of the UYS and the change of the cohesion is constant. The linear correlation is statistically significant (Adjusted R-squared = 0.997, $p < 0.05$). The coefficient 3.303 is independent of the initial consolidation stress, and thus this slope can be considered to be a characteristic of the material and to be independent of the testing conditions for a particular shear cell.

Hereon, we describe the relationship between UYS and the cohesion as the “material characteristic line”. Figure 7 also shows that the characteristic line in Fig. 7(b) can be transformed back to the shear stress-normal stress (τ - σ) diagram to describe the linearized yield loci in Fig. 7(a). In other words, while the UYS-cohesion plot (Fig. 7b) reduces the complexity of the shear cell data by collapsing all yield loci into a single line, it contains all the information needed, such as the intercept (τ_1) and the slope (φ), to transform back to the linearized yield loci family (Fig. 7a). In addition, the cohesion is highly correlated to the flow function coefficient, as discussed earlier in this section, and therefore the information regarding the preshear point, for example the major principal stress, is also stored in the UYS-cohesion plot. The material characteristic line for the individual materials we examined is reported in the Appendix. For all

the materials investigated, a linear relation between UYS and cohesion is obtained (which is statistically significant, $p < 0.05$).

The material characteristic line proposed here is consistent with previous studies. Teoman *et al.* investigated seven bulk solids and found that the angle of internal friction did not change significantly with initial consolidation stresses.[44] In addition, simulations have demonstrated that the ratio between the shear stress and the normal stress is constant when the powder flow is in the elastic-quasistatic regime.[45]

The methodology used to generate the material characteristic line can be used to compare different materials. For demonstration, the yield points at all consolidation states and the material characteristic lines of the catalyst support materials in the database are shown in figure 8. A yield point with lower value of the cohesion indicates lower inter-particulate cohesive forces during incipient flow, and a material with lower value of the slope generally experiences less frictional forces to flow.[36] While the material characteristic line describes a material at different consolidation states, the differences between the lines are independent of the initial consolidation, which enables the comparison of different materials tested under different initial consolidation stresses.

Comparison of different shear cells

To summarize the previous discussion, the UYS – cohesion plot gives a material characteristic line that is independent of the initial consolidation stress, and the $\text{ffc} - C^*$ plot enables one to classify the material. This relationship can also be used to compare measurements obtained in different types of equipment. This section compares different types of rotational shear cells to further investigate the proposed methodology. Three commercially available rotational shear

cells were compared in a previous study[31]: The RST-XS (Dietmar Schulze, Wolffenbuttel, Germany), the FT4 (Freeman Technology, Tewkesbury, Gloucestershire, UK), and the PFT (Brookfield Engineering Laboratories, Inc., Middleboro, MA, USA). The same coarse alumina and fine alumina materials described above and used in the present study were used in the previous study. 3 kPa, 6 kPa, and 9 kPa were selected as initial consolidation stresses for all the shear cells, and an additional 15 kPa was used for both FT4 and Schulze shear cell. A previous study showed that the reproducibility of measurements of the free-flowing material is lower than that of cohesive materials.[31] The yield locus measured for the coarse alumina using the Brookfield shear cell had negative cohesion values at initial consolidation stresses of 6 kPa and 9 kPa, which was an artifact of the extrapolation of the linearized yield locus, and thus were not considered here.

Figure 9 shows that the equipment characteristic E of the Schulze ($E=0.447$) and the FT4 ($E=0.485$) shear cell are reasonably similar. The Brookfield shear cell, on the other hand, had different testing performance to achieve the steady-state flow. As shown in figure 10, the angle of internal friction measured from the Schulze shear cell was larger than the one measured using the FT4 shear cell for both materials. The Brookfield shear cell gave similar results for the angle of internal friction to the FT4 shear cell for fine alumina. For both materials, the cohesion measured by the FT4 shear cell had a wider span as the initial consolidation stress increases. The UYS – cohesion plot suggests that the devices had different testing performance in achieving the incipient flow of materials as well. The difference in achieving both the steady-state flow and the incipient flow is consistent with the statistical analysis in the previously published paper.[31]

IV. Conclusion

In this study, shear cell methodologies used to characterize powder flow properties were examined. A shear cell database containing 41 powder and granular materials at 4 different initial consolidation stresses was presented. The flow indices were extrapolated based on the Mohr-Coulomb model to generate the linearized yield locus. In order to reduce the complexity of the dataset, the correlation between different parameters was examined. For the cases studied here, an inverse correlation between the flow function coefficient and the cohesion was identified. The correlation pre-factor is material independent, and increases linearly with the initial consolidation stress. A dimensionless cohesion, C^* was defined using the initial consolidation stress. The ratio between the flow function coefficient and C^* was seen to be independent of the initial consolidation stress, and can be considered to be a testing equipment characteristic value, E . The characteristic E can also be used to describe the relationship between the applied normal stress and the characteristic state when materials are critically consolidated.

The mathematical relation between the unconfined yield strength and the cohesion is a function of the angle of internal friction. For the cases studied here, by finding that the angle of internal friction did not change significantly with the initial consolidation stress for all the 41 materials in the database, a material characteristic line was generated to collapse all the yield loci for a given material into a single line independent of the initial consolidation stress. The slope of the material characteristic line is a material property required to achieve incipient flow. Material characteristic lines can be used to compare different materials, even when measurements were taken under different initial consolidation stresses.

The methodology presented here augments the shear cell data analysis through understanding the relationships of the different measurements. The identified correlation can be used to

298 compare different types of shear cells as shown in the case study presented here. For the cases
299 studied here, the comparison suggests that shear cells have different testing dynamics to achieve
300 the incipient and the steady-state flow for different materials. The results presented here are for a
301 limited set of materials and further work is needed to see if additional materials will follow the
302 same behavior. If the observed behavior carries over to other materials then the proposed
303 methods in this article could facilitate understanding of shear cell measurements and provide
304 valuable ways to analyze and compare them.

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Figure captions:

Figure 1 The schematic (a) and image (b) of the shear cell setup supplied with the FT4 Powder Rheometer (Picture source: A. Vasilenko, B. Glasser).

Figure 2 The schematic (a) and image (b) of the shear cell setup supplied with the FT4 Powder Rheometer (Picture source: A. Vasilenko, B. Glasser).

Figure 3 Correlation between flow function coefficient and cohesion (kPa) for 41 materials.

Figure 4 The power correlation coefficient of flow function coefficient and cohesion vs.the initial consolidation stresses.

Figure 5 The correlation between the flow function coefficient and the dimensionless C^* for all 41 materials under 4 different initial consolidation stresses.

Figure 6 The correlation between the log of the flow function coefficient and log of C^* for 41 materials under 4 initial consolidation stresses.

Figure 7 The yield points of maize starch are shown. (a) Yield loci of coarse alumina measured under four different initial consolidation stresses. (b) The unconfined yield strength (UYS) as a function of the cohesion.

Figure 8 Using material characteristic lines to compare different materials. The unconfined yield strength (UYS) as a function of the cohesion.

Figure 9 Comparing three shear cells by using ff_c - C^* correlation

Figure 10 Comparing three shear cells by using the material characteristic line for fine alumina (a) and the coarse alumina (b).

Figure1

Figure2

Figure 3

Figure 4

Figure 5

Figure 6

Figure7

Figure8

Figure 9

Figure 10

Table 1 Information for the 32 pharmaceutical materials in the study.

Material	Supplier
Kollidon [®] CL-F	BASF, Ludwigshafen, Germany
Kollidon [®] VA 64	BASF, Ludwigshafen, Germany
Kollidon [®] CL	BASF, Ludwigshafen, Germany
Kollidon [®] CL-SF	BASF, Ludwigshafen, Germany
Kollidon [®] 30	BASF, Ludwigshafen, Germany
Kollicoat [®] IR	BASF, Ludwigshafen, Germany
Kolliphor [®] P 188 micro	BASF, Ludwigshafen, Germany
Kolliphor [®] P 407 micro	BASF, Ludwigshafen, Germany
Soluplus [®]	BASF, Ludwigshafen, Germany
Avicel PH 101 [®]	FMC Biopolymer, Newark Delaware, US
Avicel [®] PH 102	FMC Biopolymer, Newark Delaware, US
Vivapur 101	JRS Pharma LP, IA, US
Vivapur 102	JRS Pharma LP, IA, US
Lactose monohydrate	Foremost Farms, WI, US
Acetaminophen, anhydrous basis	Mallinckrodt Inc. IL, US
Maize starch	Mitsubishi Corporation, Tokoy, Japan
Mannitol, type SD 100	Roquette Pharma, Lestrem, France
Solka Flocc	International Fiber Corporation, OH, US
Pre-gel starch	Ingredion Incorporated, IL, US
Ac-Di-Sol	FMC Biopolymer, Newark Delaware, US
Sodium starch glycolate, type A	Roquette Pharma, Lestrem, France
Microcelac [®] 100	Meggall, Wasserburg, Germany
AnhyDiCalPhos	JRS Pharma LP, IA, US
SuperTab [®] 11SD	DFE Pharma, Norten-Hardenberg, Germany
ProSolv [®] HD90	JRS Pharma LP, IA, US
Polyplasdone [®] XL	ISP Chemicals LLC. KY, US
Metformin hydrochloride	Ganules India Ltd, India
Magnesium stearate	Mallinckrodt, MO, US
API 1	Janssen Pharmaceutica N.V, Beerse, Belgium
API 2	Jassen Pharmaceutica, NV, Beerse, Belgium
API 3	Janssen Ortho LLC. Puerto Rico
API 4	Jassen Pharmaceutica N.V., Beerse, Belgium

Table 2 Information for the 9 catalyst support materials in the study.

Material	Supplier
Coarse γ -alumina	Albermarle, Amsterdam, the Netherlands
Fine γ -alumina	Albermarle, Amsterdam, the Netherlands
Fine zeolite	Albermarle, Amsterdam, the Netherlands
Molybdenum oxide (fine, sublimed type)	Albermarle, Amsterdam, the Netherlands
Zeolite Y-655 (calcined)	Albermarle, Amsterdam, the Netherlands
Zeolite Y-type CBV100	BASF Corporation, NJ, US
Titania ISK grade MC-150	BASF Corporation, NJ, US
Satintone (calcined kaolin SP-33)	BASF Corporation, NJ, US
FCC	BASF Corporation, NJ, US

Table 3 Particle size information and conditioned bulk density results for the materials used in the study.

Material	d10 (μm)	d50 (μm)	d90 (μm)	Conditioned Bulk Density (g/mL)
Kollidon® CL-F	26.77	37.31	86.89	0.29
Kollidon® VA 64	12.17	47.07	87.97	0.44
Kollidon® CL	17.90	76.06	154.90	0.42
Kollidon® CL-SF	11.26	30.14	68.94	0.21
Kollidon® 30	34.14	86.92	141.10	0.49
Kollicoat® IR	19.16	77.95	155.67	0.42
Kolliphor® P 188 micro	13.28	40.90	74.38	0.54
Kolliphor® P 407 micro	14.20	46.64	84.76	0.40
Soluplus®	197.10	325.40	476.10	0.81
Avicel PH 101®	22.93	69.98	154.89	0.34
Avicel® PH 102	34.63	113.39	220.95	0.36
Vivapur 101	20.14	64.09	131.15	0.35
Vivapur 102	31.46	123.75	224.95	0.37
Lactose monohydrate	10.32	63.54	157.78	0.66
Acetaminophen, anhydrous basis	9.93	57.40	166.00	0.41
Maize starch	9.95	14.40	24.20	0.51
Mannitol, type SD 100	59.60	97.90	147.00	0.46
Solka Floc	29.80	147.00	625.00	0.16
Pre-gel starch	8.89	36.60	104.00	0.51
Ac-Di-Sol	19.52	45.72	117.87	0.54
Sodium starch glycolate, type A	25.40	49.20	76.20	0.80
Microcelac® 100	54.10	158.00	264.00	0.51
AnhyDiCalPhos	68.60	185.00	304.00	0.75
SuperTab® 11SD	47.00	122.00	213.00	0.62
ProSolv® HD90	26.70	127.00	241.00	0.48
Polyplasdone® XL	9.65	23.60	54.16	0.42
Metformin hydrochloride	50.46	136.75	248.144	0.52
Magnesium stearate	14.89	62.33	149.30	0.27
API 1	9.66	63.60	185.00	0.36
API 2	3.15	11.90	24.40	0.37
API 3	14.60	47.10	95.90	0.36
API 4	9.75	41.50	153.00	0.36

Coarse γ -alumina	11.16	59.37	122.19	0.97
Fine γ -alumina	0.99	4.07	11.46	0.31
Fine zeolite	0.94	3.85	5.81	0.86
Molybdenum oxide	0.76	3.71	10.31	1.4
Zeolite Y-655 (calcined)	0.80	2.33	7.59	0.31
Zeolite Y-type CBV100	0.77	2.99	10.44	0.25
Titania ISK grade MC-150	0.69	2.99	10.13	0.35
Satintone (calcined kaolin SP-33)	0.92	6.09	21.14	0.52
FCC	38.48	79.65	134.30	0.83