BROOKFIELD POWDER FLOW TESTER

Operating Instructions

Manual No. M09-1200
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**Appendix A:** Overview of Powder Flow Properties
I. INTRODUCTION

There is a need throughout industry to characterize powder flow properties and flow behavior. The Brookfield POWDER FLOW TESTER (PFT) is a precision instrument of robust design that satisfies this need and can be used to measure, display and print out flow results at specified compaction loads. Potential users include R&D Departments, QC laboratories, Incoming Inspection for raw materials, and government/university organizations.

The principal of operation of the PFT is to drive a compression lid vertically downward into a powder sample contained in an annular shear cell. The powder sample has a defined volume and the weight of the sample is measured before the start of the test. A calibrated beam load cell is used to control the compaction stress applied to the powder. The annular shear cell is then rotated at a defined speed and the torque resistance of the powder in the shear cell moving against the powder in the stationary lid is measured by a calibrated reaction torque sensor. The geometries of the lid, shear cell, rotational speed of the cell, and the compressive loads applied to the powder all contribute to the calculations which determine the flow-ability of the powder.

The intended uses for the PFT include:
• Pass/fail tests to certify material quality prior to shipment
• Providing meaningful numbers that guide how powder will handle in silos, hoppers, feeders, filling machines and the like
• Benchmarking for daily production lots or for comparing flow behavior of new formulations against existing product
• Creating data bases for choice of production lines, sourcing, formulation and second source suppliers
• Producing quantitative results that can be used for design of processing plants and equipment

There are several powder flow properties which the PFT measures to categorize flow-ability. Note that these properties, which may vary with changes in temperature and humidity, include:
• Unconfined failure strength
• Major Principal Consolidating Stress
• Tensile strength
• Angle of internal friction
• Angle of wall friction
• Cohesive strength
• Bulk density

The most recognized indication of powder flow-ability is the unconfined failure strength when viewed as a function of the consolidating stress. Wall friction, internal friction, and bulk density are also commonly used to relate measurements to flow behavior. Appendix A provides a more detailed explanation of these properties and how they are measured.
I.1 Components

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>PART NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>The following items are included with your instrument:</td>
<td></td>
</tr>
<tr>
<td><strong>Powder Flow Tester</strong></td>
<td></td>
</tr>
<tr>
<td>Powder Flow Tester 115V AC <em>or</em></td>
<td>PFT115</td>
</tr>
<tr>
<td>Powder Flow Tester 230V AC</td>
<td>PFT230</td>
</tr>
<tr>
<td>Powder Flow Pro Software with USB cable</td>
<td>PFT-609</td>
</tr>
<tr>
<td>Power Cord 115 Volt <em>or</em></td>
<td>DVP-65</td>
</tr>
<tr>
<td>Power Cord 230 Volt</td>
<td>DVP-66</td>
</tr>
</tbody>
</table>

**Required Accessories** which are included with the instrument

Standard Accessory Kit  
(includes PFT-400, PFT-500, PFT-507, PFT-600, PFT-611, PFT-612, CP-23)  
Sample Trough Aluminum 230 cc (6 inch diameter)  
PFT-400  
Vane Lid 304 S/S 33 cc (6 inch diameter)  
PFT-500  
Wall Lid 304 S/S 2B finish 230 cc (6 inch diameter)  
PFT-507  
Catch Trays & Shaping Blade (230 cc/263cc, 6 inch)  
PFT-600  
Powder Scoop  
PFT-611  
Cleaning Brush  
PFT-612  
3/8” Wrench [for leveling]  
CP-23  
Operator Manual  
M09-1200

**Optional Accessory items** that can be ordered for use with the Powder Flow Tester

include the following:

Sample Trough Aluminum 230 cc (6 inch diameter)  
PFT-400  
Sample Trough [less screen] (230 cc, 6 inch)  
PFT-401A  
Perforated Screen (230 cc, 6 inch)  
PFT-440  
Inner Catch Tray with Shaping Tool (230 cc, 6 inch)  
PFT-6Y  
Outer Catch Tray (230 cc, 6 inch)  
PFT-8  
Humidity Sensor with interface cable  
PFT-607Y  
RTD Temperature Sensor with interface cable  
DVP-94Y

I.2 Utilities

| Input Voltage:               | 90-265 VAC  |
| Input Frequency:             | 47-63 HZ    |
| Power consumption:           | 150VA       |
| Fuse:                        | Two 2 AMP, 5 x 20mm, FAST-ACTING |

<table>
<thead>
<tr>
<th>Power Cord Color Code:</th>
<th>United States</th>
<th>Outside United States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot (live)</td>
<td>Black</td>
<td>Brown</td>
</tr>
<tr>
<td>Neutral</td>
<td>White</td>
<td>Blue</td>
</tr>
<tr>
<td>Ground (earth)</td>
<td>Green</td>
<td>Green/Yellow</td>
</tr>
</tbody>
</table>

Main supply voltage fluctuations are not to exceed +/- 10% of the nominal supply voltage.
I.3 Specifications

Load for vertical axis compression:
7 kg Accuracy: +/-0.6% FSR

Torque: +/- 7.0 N•m Accuracy: +/-1.2% FSR

Distance: Accuracy +/- 0.3mm

Speeds:
Torsional speeds: 1 revolution per hour (RPH) up to 5 RPH. Default setting 1 RPH.
When using Keypad: 10 RPH

Axial speeds: 0.1mm/sec up to 5mm/sec. Default setting 1 mm/sec
When using Keypad: 5mm/sec

Temperature Sensing: -20°C to 120°C (Requires optional temperature probe, Part No. DVP-94Y)

Humidity Sensing: 10% to 95% RH +/- 5% (Requires optional humidity sensor, Part No. PFT-607Y)

Output: USB Port or RS-232 compatible Serial Port

Environmental Conditions: 0°C to 40°C temperature range (32°F to 104°F)
20%-80% relative humidity, non condensing atmosphere

Use: Intended for indoor use only. Altitude up to 2000m

Dimensions: 36.2cm (14 1/4") W x 39.7cm (15 5/8") D x 67.6cm (26 5/8") H

Weight: 34 kg (75 lb)

Minimum System Requirements for the Powder Flow Pro software:

Microprocessor: 2GHz processor
Memory: 512 MB of RAM
Hard Drive Space: 30 MB available
Video: 1024 x 768 resolution, 128 MB of graphics memory
Operating System: Windows XP, Vista
Communications Port: One USB or RS-232 port

I.4 Safety Symbols and Precautions

Safety Symbols

⚠️ Refer to the manual for specific warning or caution information to avoid personal injury or damage to the instrument.

⚠️ Keep hands, fingers and other body parts clear of moving parts when operating instrument.
Functional Earth Terminal- Main power entry module must have an earth conductor, to ensure against electronic failure.

Precautions

⚠️ If this instrument is used in a manor not specified by the manufacturer, the protection provided by the instrument may be impaired.

⚠️ This instrument is not intended for use in a potentially hazardous environment.

⚠️ In case of emergency, turn off the instrument and then disconnect the electrical cord from the wall outlet.

⚠️ The user should ensure that the substances placed under test do not release poisonous, toxic, or flammable gases at the temperature which they are subjected to during the test.

⚠️ The torque reaction sensor will be damaged if more than 150% of the FSR torque (+/- 7.0 N•m) is applied.

I.5 Back Panel

Figure I-1: Back Panel
1. USB Type B port
   Use with USB Cable P/N DVP-202 to connect instrument to a computer. Cable USB 2.0 A Male to B Male.

2. RS-232 Serial Port
   Use with RS-232 Cable P/N DVP-80 to connect instrument to a computer.

3. Temperature Probe Plug
   4-Pin plug. Use with Temperature Probe P/N DVP-94Y.

4. Humidity Sensor Plug
   3-Pin plug. Use with P/N PFT-607Y.

5. Power entry module:
   ON/OFF switch-fused (see Utilities section) Voltage 90-265 VAC.

6. Lift Channel positions for handling instrument. Recommend two people for movement of instrument due to heavy weight.

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**I.6 Key Functions**

![Figure I-2: Control keys for standalone mode](image)

**Figure I-2: Control keys for standalone mode**

Standalone mode is used only for positioning of the compression lid assembly and the sample trough drive. Software is required for all other operations.

**Keypad**

↑ This key is used to move the compression plate assembly UP away from the sample trough drive assembly.

↓ This key is used to move the compression plate assembly DOWN towards the sample trough drive assembly.
This key is used to rotate the sample trough drive assembly clockwise.

This key is used to rotate the sample trough drive assembly counter-clockwise.

**I.7 Emergency Stop - Reset**

This button is used to abort a test in case of an emergency condition. All operations will halt when the button is depressed. Rotate the button to reset, which allows the instrument to return to normal operation.

**I.8 Installation**

1. Prepare a clean and level surface.

   *Note:* This instrument is a sensitive load measuring device. It should be installed on a clean, solid, level bench surface which is free from external vibrations.

2. Unpack the Powder Flow Tester (PFT) from the shipping container. To do this remove the top and front panels of the crate.

3. Remove the instrument from the shipping package.

   ! The PFT weighs 34 kg (75 lb). Use caution when lifting the unit out of the packaging.

4. Place the PFT on a sturdy, level surface.

5. Position the instrument so the AC power switch is easily accessible.

   ! The AC input voltage and frequency must be within the appropriate range as shown on the model and serial tag of the instrument (located on the back of the PFT).

*Figure I-3: Back View of Lift Points*
6. Make sure the AC power switch located in the back of the instrument is in the off position. Connect the power cord to the socket on the instrument and plug it into the appropriate AC line. Turn the power switch on.

7. Remove the "U" shaped foam piece from the area directly above the Compression Plate.

![U-Shaped Shipping Foam]

Figure I-4: Shipping Foam Removal

8. Press the Up arrow key to raise the Compression Plate.

9. Remove the Sample Trough by lifting it up off of the Drive Disc on the instrument.

10. Remove the foam piece in the Trough.

11. Remove any additional components from the shipping package. Save the shipping container and packaging for future use.

12. Connect the USB cable to the slot designated for the USB in the back of the instrument. If RS-232 is used instead of USB, connect the cable to the RS-232 slot.

13. Connect the other end of the USB RS-232 cable to a computer.

14. The tester must be leveled. Open the bubble level access door. Adjust the four feet until the bubble is centered within the circle of the bubble level; also check to ensure the instrument is stable. Use a 3/8" wrench (supplied in the Standard Accessory kit) or tilt the instrument to adjust the feet by hand.

### I.9 Cleaning

**Instrument and Keypad:**
Clean with a dry, nonabrasive cloth. Do not use solvents or cleaners

**Troughs/Lids/Catch trays:**
These accessories are made from a variety of materials ranging from metals (stainless steel, Aluminum) to plastics (Tivar 88, Teflon). Clean with a nonabrasive cloth using solvents that are appropriate for both the sample material and the material of the accessory.

⚠️ Do not apply excessive force to the compression lid assembly or the sample trough drive assembly on the instrument. Damage may occur to the components.

⚠️ Some of the accessories have sharp edges.
II. QUICK START PROCEDURE

1. Level the instrument.
2. Turn on the power to the instrument. The switch is on the back side.
3. Open Powder Flow Pro software application on PC. Go to setup menu. Establish communication with instrument in the Setup Tab. Select USB or RS232, whichever is appropriate.
4. Record weight of Trough (e.g. 702.34 grams).

![Figure II-1: Trough](image)

5. Attach the Outer Catch Tray outside the trough. Insert the Inner Catch Tray with Shaping Tool inside the Trough.
   
   **Note:** Align one hole in the bottom of the Inner Catch Tray to the pin in the Trough.

![Figure II-2: Inner and Outer Catch Tray](image)

6. Fill the Trough with powder and level with the Shaping Tool; use the Shaping Tool with plow blade for test using a Vane Lid; use the Shaping Tool with the flat blade for test using a Wall Lid. Remove both catch trays.

![Figure II-3: Shaping Blade in Plow Position](image) ![Figure II-4: Shaping Blade in Flat Position](image)
7. Record the weight of the powder and the Trough. Subtract the weight of the Trough to determine the weight of the sample.

8. Install the Trough onto the instrument. Outer Catch Tray can be installed on Trough to catch spillage during test.

9. Attach the appropriate Lid to the instrument. Use Vane Lid for the Flow Function test and Time Consolidated Flow Function test. Use the Wall Friction Lid for the Wall Friction test and the Bulk Density test.
10. Go to the Powder Flow Pro software application. Enter the sample information and the weight of the powder sample on the main screen.

![Sample Identification and Test Selection](image1)

**Figure II-8: Sample Identification and Test Selection**

11. Select the desired test method, e.g. Flow Function. Default settings for number of Consolidation Stresses (3) and number of Over Consolidation Stresses (3) will automatically appear. "Even Spacing" for the Consolidation Stresses is also the default setting.

Push DISPLAY TEST STRESSES button for a detailed list of the test steps.

![Flow Function Test](image2)

**Figure II-9: Flow Function Test**

12. Start test by pushing RUN TEST button. Test runs automatically to completion. Save test results under file name which you selected when entering test sample information.

13. After completion of test, use manual control on face of instrument to raise Lid (UP ARROW). Remove Lid from instrument. Remove Trough from instrument. Clean off excess powder on instrument.

III. SAMPLE PREPARATION AND HANDLING

Accurate and repeatable test results require attention to condition of the sample prior to testing and the use of proper laboratory procedures during sample preparation. This section explains the details.

III.1 Sample Issues

The Flow Function and Time Consolidated Flow Function Tests require slightly over 260cc of sample material. Allowing for spillage during sample preparation and testing, best practice suggests that you start with at least 300cc of sample material. If repeated tests will be performed on the same sample, then 500cc or more are recommended.

Note the condition of the sample prior to testing. Storage in a bag or sealed container will offer protection, whereas leaving the sample on the counter in an open bag or container will expose the sample to the environmental conditions in the test area.

Moisture in the sample is one of the primary factors to be aware of when working with powders because it can have a serious impact in making the powder more cohesive, and therefore less free-flowing. The potential for the powder to take on moisture (either by adsorption or absorption) is a factor that can affect test results. The Powder Flow Tester has the optional capability to accommodate a humidity sensor (Part No PFT-607Y) which plugs into the back of the instrument.

Temperature may have some impact, but certainly plays less of a factor compared to humidity. The Powder Flow Tester has the optional capability to accommodate a temperature sensor (Part No DVP-94Y) which also plugs into the back of the instrument.

Consider all environmental issues in your test area before proceeding with your test plan.

III.2 Sample Trough

Figure III-1 shows the standard Sample Trough (Part No PFT-400) which comes with the PFT. The Trough is made of aluminum and is of annular shape for containment of sample. In the bottom of the Trough is a Perforated Screen (Part No PFT-440) which holds the sample in place so that the powder particles on the bottom do not slide on the smooth metal surface when the Trough rotates.

Figure III-1: Sample Trough
The Trough has a working volume to hold 230cc of sample material when the material is level with the top surface of the Trough. When used with the Vane Lid, the additional volume required for the Lid increases the total sample size to slightly more than 260cc of material.

### III.3 Lid Selection

The PFT comes with two types of Lids of annular design as shown in Figure III.2. The bottom side of the Lid is shown in each case; these surfaces make contact with the powder during the test.

**Figure III-2: Bottom side of Vane Lid and Wall Friction Lid**

The Vane Lid (Part No PFT-500) has 18 small compartments which trap the powder particles and cause them to shear against the powder particles in the Trough. The Vane Lid is made of 304 s/s and has a 15.25cm (6-inch) outer diameter.

The Wall Friction Lid (Part No PFT-507) has a smooth bottom surface made of 304 s/s with 2B finish, which slides over the powder particles in the Trough during the test, thereby measuring the friction of powder against the surface material of the Lid. The surface can be made of other materials, depending on your preference; 316 s/s Mild steel and Tivar 88 are two other common options. The choice typically depends on the material of construction that will be used in the storage bin, hopper or containment vessel that stores the powder in your processing plant. Contact Brookfield or your authorized dealer for alternative choices on the surface material of construction for the Wall Friction Lid.

The top sides of the Lids have two pins which engage with the Compression Plate on the instrument during the attachment process. Two release buttons must be pressed in order for the Lid to engage and successfully attach to the Compression Plate.

**Figure III-3a: Top Side of Lid Showing Engagement Pins**
III.4 Outer Catch Tray

The Outer Catch Tray, shown in Figure III.4, provides a convenient apron around the trough for collection of sample material which spills over the edge of the Trough during sample loading and test execution. Center it over the Trough and observe that it fits conveniently on the outer lip of the Trough.
III.5 Inner Catch Tray with Shaping Tool

The Inner Catch Tray is used to distribute the sample evenly in the Trough. It fits into the annular opening on the Trough. See Figure III.5.

![Figure III-5a: Inner Catch Tray with Shaping Blade in Plow Position](image)

![Figure III-5b: Inner Catch Tray Inserted Into the Annular Opening of the Trough](image)

The Shaping Tool which is affixed to the center of the Inner Catch Tray is rotated by hand to distribute the sample. Note that the Shaping Tool can be removed by unscrewing the thumb screw that secures it to the Inner Catch Tray. This allows the user to choose the type of scraper blade that is needed for sample distribution. Note that one side of the Shaping Tool is flat (for use with Wall Lid in the Wall Friction and Bulk Density tests) and the other is curved which permits mounding of the sample in the trough (for use with the Vane Lid in the Flow Function and Time Consolidated Flow Function tests). See Figure III-6.

![Figure III-6a](image)

![Figure III-6b](image)

Figures III-6a and III-6b Show the Two Positions of the Shaping Blade

III.6 Loading the Trough with Sample

Weigh the Trough before filling it with sample material. Record the value.

Place the Outer Catch Tray into position on the Trough. Place the Inner Catch Tray into position on the Trough. Use the Powder Scoop (Part No PFT-611), which comes with the instrument, to place the powder sample in the Trough. Any spillage is conveniently captured by the Inner and Outer Catch Trays. When sufficient sample has been placed in the Trough, rotate the Shaping Tool on the Inner Catch Tray to distribute the sample evenly around the Trough. Rotate in a
clockwise direction until the sample is completely distributed. Then rotate in a counter-clockwise direction to remove excess sample.

Remove the Inner and Outer Catch Trays from the Trough. Return excess sample material in the Catch Trays to the container form which the powder came or throw it away in accordance with your lab policy.

### III.7 Placement of the Trough and Lid on the Instrument

Take the Trough loaded with sample material and weigh it again. Subtract the weight of the Trough to obtain the weight of the sample material. Enter this value into the Sample Information section of the main screen on the Powder Flow Pro software.

Make sure that the Compression Plate on the instrument is in the upmost position. Use the Up arrow on the instrument control panel to reposition the Compression Plate if necessary.

Place the Trough on the Drive Disc of the instrument so that the center of the Trough aligns with the pin in the center of the Drive Disc. Rotate the Trough by hand until the pin on the outer edge of the Drive Disc engages one of the holes on the bottom of the Trough’s outer edge. When this occurs, the Trough will lie secured in a flat position, centered on the drive plate.

Place the Outer Catch Tray in position around the Trough. This serves to catch any spillage of the sample material when the test is running.

Attach the appropriate lid to the Compression Plate on the instrument. You may choose to do this before placing the Trough on the instrument. It is simply a matter of operator preference.

⚠️ The Lids are sharp. Be careful when installing and removing.

The test is now ready to begin. Refer to the section on Powder Flow Pro Software for details on running tests from your PC. When the Run Test button is pushed on the main screen, the Lid will automatically descend onto the Trough, pausing for a brief period of time just prior to making contact with the powder sample in order to perform an autozero check.

### III.8 Removal of Trough and Lid from Instrument

When the test is complete, the Lid will automatically raise up a small distance off of the Trough. This is a visual indication that the test has ended. Push and hold the manual control for the UP arrow on the instrument control panel until the Lid has raised to its upmost position. Then disengage the Lid from the Compression Plate. Clean the excess powder that clings to the Lid.

Remove the Outer Catch Tray from the Trough and dispose of the excess powder in the Tray. Remove the Trough from the instrument and dispose of the powder sample in accordance with lab procedure. Clean the Trough with the Cleaning Brush (Part No PFT-612) which came with the instrument. Note that the perforated screen may require special attention with powder particles that have been trapped in the openings.
III.9 Cleanup

The Cleaning Brush serves to remove excess powder from the Trough and Lid. This may be adequate for repeated testing of the same powder types where the potential for cross-contamination between samples is not really an issue.

For more thorough cleaning, the use of an air hose, water, or a cleaning solvent may be desired. When using a liquid for cleaning, make sure to dry the Trough and Lid thoroughly so that moisture contamination does not become an issue with the next sample.
IV. POWDER FLOW PRO SOFTWARE

Software (Part No PFT-609A) and USB cable for connection to a PC are provided with the PFT Powder Flow Tester in order to operate the instrument, collect data, perform analyses, store data files, and export data to other programs, such as Excel. The name of the software is Powder Flow Pro and is one of several programs listed on the CD that comes with the PFT. The other programs on the CD do not pertain to the PFT.

Connect the USB cable to the PFT and to your PC. Turn on the PFT using the power switch on the backside of the instrument. Load the CD onto your PC and start the Powder Flow Pro program.

IV.1 Main Screen and Setup Tab

Upon startup, the main screen comes up as shown in Figure IV-1.

Figure IV-1: Main Screen

Details on sample type and test method are entered on this page. However, before proceeding, make sure that the program is communicating with the PFT by clicking on the Setup Tab. The Setup Screen is shown in Figure IV-2.
Press the “Search” button. If the instrument is correctly connected to your PC with the USB (or RS-232) cable, the green light will come on and the type of communication port being used will be identified, in this case, USB.

While on this page, it is also possible to adjust the measurement units, axial speed for moving the lids up and down, and torsional speed for rotating the trough. Default values are set at the factory for measurement units and operating speeds. If you decide to change any of these values, you must then shut down the Powder Flow Pro program and start it up again in order for the changes to take effect.

Click the Test Tab which brings you back to the Main Screen.

**IV.2 Sample Information**

The left column on the Main Screen is used to enter information on the sample that you are testing. See Figure IV-3.
There are 5 boxes in which to make entries:

a) Sample Identification  e.g. Flour
b) Product Name  e.g. Lorenzo’s Long Grain Brown Rice
c) Batch Number  e.g. List your control number for the sample or, perhaps, the date time if you don’t use control numbers.
d) Sample Number: You have the choice to allow the software to increment each test with a sequential control number (the default setting), or you can choose to set this value by clicking the “Set Manually” button.
e) Weight:  Enter the weight of the sample. The default setting is grams.

Sample Notes can be entered in the box on the bottom half of the left column on the Main Screen. This may provide information, for example, on how the sample was prepared or how long it has been in storage.

Click on the disc icon above “Sample Identification” to save the information that you have just entered on your sample.

### IV.3 Test Type

The middle column on the Main Screen is used to select the type of test that you want to run. See Figure IV-4.
Choose one of the 4 tests that are listed under “Test Types”. The first two tests require the use of the Vane Lid. The last two tests require the use of the Wall Friction Lid. Details on information that you must enter for each test follow:

a) **Flow Function**
   The user can set the number of consolidation stresses to test, whether to space the consolidation stresses evenly or geometrically, the number of over consolidation stresses to run at each consolidation stress, whether to repeat each stress measurement, and whether to test at the tangent to the Unconfined Mohr Circle.

b) **Time Consolidated Flow Function**
   The user can set the amount of time to consolidate at each consolidation step, whether to use a new sample for each time consolidation, the number of consolidation stresses to test, whether to space the consolidation stresses evenly or geometrically, the number of over consolidation stresses to run at each consolidation stress, what stress to apply during time consolidation, whether to repeat each stress measurement, and whether to test at the tangent to the Unconfined Mohr Circle.

c) **Wall Friction**
   The user can set the material of the cell lid, the number of displacement levels to test
at, whether to space the displacement levels evenly or in a doubling progression, the number of stresses to run at each displacement level, and what stress to apply during wall displacements.

d) **Bulk Density Curve**
   The user can set the number of stress setpoints.

Once the test details have been finalized, click on the “Display Test Stresses” button to view the number of steps in your program as shown in Figure IV-5. In this case a flow function has been selected. The two columns on the right show the sequence for the consolidation stresses and the corresponding overconsolidation stresses that will be applied. Note that the time estimate for the test to run is displayed in the window at the top right of the Main Screen. Units are hours: minutes:seconds.

![Figure IV-5: Right Column on Main Screen](image)

Click on the disc icon above “Test Type” to save the information that you have just entered on test type.

**IV.4 Test Execution**

To start the test, click the “Run Test” button on the Main Screen. The Lid will descend to a position slightly above the sample in the Trough; the instrument will perform an autozero; then the Lid will make contact with the sample and the test begins.
The Raw Data Tab on the Analysis Screen will automatically come up and show the axial load test data and the torsional load test data. See Figure IV-6. The axial load units are shown on the Y-axis on the right of the graph (green color) and the torsional load units are shown on the Y-axis on the left of the graph (red color).

**Figure IV-6:** Image of Test Data on Analysis Screen Showing One Full Cycle of a Consolidation Stress and Two Associated Overconsolidation Stresses

Details on test method execution for each of the 4 test types are shown in the following figures.
Load powder, start test

Apply consolidation load
Shear to steady state

Re-apply consolidation load
Measure peak

Apply over-consolidation load
Measure peak

Re-apply consolidation load
Shear to steady state

(if option chosen)

Calculate tangent load
Apply tangent load
Measure peak
Re-apply consolidation load
Shear to steady state

Re-apply consolidation load
Measure peak

End test, process results

Loop until all increasing over-consolidation loads are tested

Loop until all repeat over-consolidation measurements are taken

Figure IV-7: Flow Function Test Algorithm.
Load powder, start test

Apply consolidation load, shear to steady state

Re-apply consolidation load, measure peak

Apply over-consolidation load, measure peak

Re-apply consolidation load, shear to steady state

(if option chosen)

Calculate tangent load

Apply tangent load, measure peak

Re-apply consolidation load, shear to steady state

Re-apply consolidation load, measure peak

Leave for time consolidation period $T$, apply load $\sigma_1$

Apply Time over-consolidation load, measure peak

Load fresh powder sample (if option is chosen)

End test, process results

Loop until all increasing over-consolidation loads are tested

Loop until all repeat over-consolidation measurements are taken

Loop until all increasing consolidation loads have been tested

Figure IV-8: Time Consolidated Flow Function Algorithm
Load powder, start test

Apply compaction load, measure lid position

Apply consolidation load, shear to steady state

Re-apply consolidation load, measure peak

Apply Wall consolidation load, rotate for required shear displacement

End test, process results

Loop until all increasing compaction loads are taken

Loop until all reducing consolidation loads are tested

Loop until all increasing wall displacements are measured

**Figure IV-9: Wall Friction Test Algorithm**
Load powder, start test

Apply compaction load, measure lid position

End test, process results

Loop until all increasing compaction loads are taken

**Figure IV-10: Bulk Density Test Algorithm**

Throughout the test, a green light will flash and the estimated time to completion will continue to count down and be displayed in the top right window on your screen. The algorithms which measure peak torsional stress and steady state torsional stress have optimization functions built into the realtime data analysis. The net result is that some of the test time may be reduced because the steady state value is achieved earlier than the allotted test time for a specific step(s).

At any time during the test, the user can return to the Main Screen to observe the detailed test step display and note which step is in progress.

When the test is completed, the flashing green light will disappear, the “Estimated Test Time” window will be blank, and the Lid will raise up slightly off the sample.

**IV.5 How to Stop the Test**

At any time during the test, the user can abort the test by clicking on the Stop icon in the upper left corner of the main screen or by clicking the Stop Test button, which lights up on the Main Screen once the test starts. See Figure IV-11.
If the user pushes the Emergency Stop button on the instrument, the button must be reset in order for the instrument to communicate with the Powder Flow Pro program. Rotate the button in a clockwise direction as far as it will go, then release the button.

When the test is stopped by one of the above actions, the Lid will lift up from the Trough, which is no longer rotating. The test cannot be resumed at the step where you stopped the test. The data cannot be saved. You must start all over. If the sample had been compacted, best practice is to replace the sample with fresh material.

IV.6 Analysis Section

IV.6.1 How to Save Data

Once the test has completed, you have the choice to save the raw test data and/or the calculated stress data (click on the Stress Data Tab). Most users will choose to save only the calculated stress data, since this is the basis for computing the desired output parameters: flow curve, friction angle curve, density curve and critical hopper dimensions.

The raw test data consists of 100 data points per second, which means that the file size can be large, especially for tests of lengthy duration. For this reason, most users may choose not to save raw data.

To save the calculated stress data, click the disk icon on the toolbar. To save the raw data, click the box called “Save Raw Data” located next to the disk icon, then click the disk icon; this will save both the raw data and the calculated stress data.

IV.6.2 Choices for Data Display

Figure IV-12 shows the available choices for data that can be displayed (Raw Data, Stress Data, Flow Data or Friction Angle, Density Curve, Hopper Design) and the format for displaying the data (Graph, Results, Data). Click on the boxes that you require and the corresponding data and/or graph(s) will be shown.
Figure IV-12: Options for Data Output Display

Note that the third tab on the Analysis screen can be either “Flow Data” or “Friction Angle”, depending on the type of test that is run. The former appears when Flow Function and Time Consolidated Flow Function are selected. The latter appears when Wall Friction is selected.

When the test for Bulk Density Curve is selected, the tabs which appear include Raw Data, Stress Data, and Density.

Details on the information that can be viewed under each tab follows:

a) Raw Data:
   All test types display the specific fields chosen for the raw data graph. All the raw data also appears in the “Custom Tab” in tabular format.

b) Stress Data:
   All applicable Peak and Steady State stresses are shown. In addition, the following is displayed for each type of test:
   - Flow Function Test data shows a locus line for each Consolidation Stress setpoint, with corresponding Unconfined and Over consolidated Mohr circles, and a Steady State locus line. For the Steady State locus, the gradient, angle, and cohesion are reported. For each Consolidation Failure Locus the Major Principal Consolidation Stress, Unconfined Failure Strength, Angle of Internal Friction, gradient, angle, cohesion, and density are reported.
   - Time Consolidated Flow Function Test data shows all the instantaneous locus lines and circles, plus a time consolidated locus line for each Consolidation Stress setpoint with its corresponding Unconfined Mohr circle. All instantaneous flow results are reported; each time consolidated locus reports its Unconfined Failure Strength and cohesion.
   - Wall Friction Test shows one locus line for each Displacement setpoint and one Maximum Wall locus, including the gradient, angle, and cohesion for each locus line.
   - Density Test data: Not applicable.

c) Flow Curve:
   - Flow Function Test shows the curve of Unconfined Failure Strengths versus
Major Principal Consolidation stresses and reports the Flow Function gradient and intercept, the critical Arching and Rat-hole stress, and the Flow Index for a given stress.

- Time Consolidated Flow Function Test data shows one instantaneous curve and one time consolidated curve and reports the same results as the Flow Test, but shows one set of results based on the instantaneous Flow Function and one based on the time consolidated Flow Function.

- Wall Friction Test data: Not applicable.
- Density Test data: Not applicable.

d) Friction Angle Curve:
- Flow Function Test data shows one curve based on the Effective Angle of Internal Friction for each Consolidation setpoint and reports the Effective Angle of Internal Friction for the critical Arching stress and critical Rat-hole stress.
- Time Consolidated Flow Function Test data reports the instantaneous Flow Function results along with the Effective Angle of Internal Friction for the Time critical Arching stress and Time critical Rat-hole stress.
- Wall Friction Test data shows one Wall friction angle curve for each displacement setting and one curve based on the Maximum Wall locus. The data tab lists all Wall Friction angles, at each stress setpoint at each displacement setting, including the Maximum Wall Friction at each stress setpoint.
- Density Test data: Not applicable.

e) Density Curve:
- Flow Function Test data shows one curve based on the initial fill density and the densities measured at the Steady State stress values. The Density for the critical Arching stress and critical Rat-hole stress are also reported.
- Time Consolidated Flow Function Test data reports instantaneous results along with the Density for the Time critical Arching stress and Time critical Rat-hole stress.
- Wall Friction Test data shows one curve based on the initial fill density and the compactions at the beginning of the test.
- Bulk Density Curve Test data shows one density curve including initial fill density.

f) Hopper Design:
- Flow Function Test data shows Arching and Rat-hole dimensions based on critical values picked off of the above Flow Test curves, with the option to use a separate density file. One Hopper half angle (user has selected whether it is a conical or wedge hopper) is calculated using this file and the Maximum Wall locus from a chosen Wall Test file.
- Time Consolidated Flow Function Test data shows two sets of Arching and Rat-hole dimensions, one based on the instantaneous flow function curve, and one based on the applicable time consolidated flow function curves. There is an option
to use a separate density file. Two Hopper half angles are calculated, both using the
Maximum Wall locus of the chosen Wall Test file, but one using instantaneous flow
function data and one using time consolidated flow function data.

- Wall Friction Test data calculates several Hopper half angles, one for each
  Displacement setpoint, each using the flow curves from the chosen Flow Test file.
  Arching and Rat-hole dimensions are not applicable.

- Density Test data: Not applicable.

IV.6.3 How to Compare Data

Comparisons between data files are done using one condition from each file. There are several
output parameters to consider. Available choices are shown in Figure IV-13. For example, only
the Time consolidated values from a Time Consolidated Flow Function test are compared to
other files. The instantaneous values for the Time Consolidated Flow Function test are not used
in the comparison.

![Figure IV-13: Parameter Choices for Data Output on Test Files](image)

*Figure IV-13: Parameter Choices for Data Output on Test Files*
a) Flow Function Curves:
   - For Flow Function Test data, use the regular Flow Function for comparisons. This reports the gradient, intercept, critical stresses, and Flow Index based on this Flow Function.
   - For Time Consolidated Flow Function Test data, use the time consolidated flow curve for comparisons. This reports the gradient, intercept, critical stresses, and Flow Index based on this Time Consolidated Flow Function. If you want to compare the instantaneous and time curves within a single Time Test data set, you can do so in the Analysis section.
   - Wall Test data: Not applicable.
   - Density data: Not applicable.

Refer to Figure IV-14 for an example of several Flow Functions Tests on Limestone Sand.

![Figure IV-14: Comparison of Flow Function data in Limestone Sand](image)

b) Friction Angle Curves:
   - For Flow Function Test data, use the Internal Angle for comparisons. This reports the Internal Angles at critical stresses based on this curve.
   - Time Consolidated Flow Function Test data, use the instantaneous Internal Angle for comparisons. This reports the Internal Angles at the Time critical stresses based on this curve. If you want to compare the instantaneous and time critical stresses within a single Time Test data set, you can do so in the Analysis section.
   - For Wall Friction Test data, use the Wall Angle curve from the Maximum Wall Locus for comparisons. If you want to compare Wall Angle curves at different displacements within the same data set, you can do so in the Analysis section. If a Wall Test data set is part of the Comparison, no angles are reported for critical stresses, because the critical stresses for the Wall file are unknown.
   - Density Test data: Not applicable.
c) Bulk Density Curves:

- For Flow Function Test data, use the densities measured at the steady state of each locus line for comparisons. This reports densities at critical stresses for arching and rat-holing.
- For Time Consolidated Flow Function Test data, use the instantaneous density curve for comparisons. This reports densities at critical stresses for arching and rat-holing.
- For Wall Friction Test data, use the density data from the compactions at the start of the test for comparisons. If a Wall Test data set is part of the Comparison, no densities are reported for critical stresses, because the critical stresses for the Wall file are unknown.
- For Bulk Density Test data, use the density data from the compactions for comparisons. If a Density Test data set is part of the Comparison, no densities are reported for critical stresses, because the critical stresses for the Density file are unknown.

d) Hopper Design:

- For Flow Function Test data, use the critical values from the regular flow function, friction angle, and bulk density curves for comparisons. There is no external Density file option, values are taken from within the Flow Function Test data file.
- For Time Consolidated Flow Function Test data, use the critical values from the time consolidated flow curve for comparisons. Use the instantaneous friction angle and density curves. There is no external Density file option. If you want to compare instantaneous and time consolidated outlet sizes within one Time Test data set, you can do so in the Analysis section.
- Hopper Half Angle would not be included in the Comparison section, because each calculation requires specifying two data sets, a Flow Function (or Time Consolidated Flow Function) Test and a Wall Friction Test data set.

IV.7 Statistics Page

Statistics can be done on results which have one value per data file. For example, statistics can be done on the Steady State Locus gradient of 10 Flow Function Test data sets, because each data set has only one Steady State Locus gradient. Statistics could not be done on the Time Consolidation Flow Function Failure Locus gradient, because there are several Consolidation Failure Loci per data set.

See Figure IV-15 for an example of a Statistical Report.
The following statistical reports can be created for the types of test data as indicated:

- **Statistics for Flow Function and/or Time Test data sets:**
  Statistics can be done on the following results: Steady State Locus gradient, angle, and cohesion; Flow Function gradient, intercept, and Flow Index at a given stress; Arching dimension and critical arching stress, friction angle, and density; Rat-hole diameter and critical rat-hole stress, friction angle, and density; fill bulk density and maximum bulk density.

- **Wall Friction Test data sets:**
  Statistics can be done on the Maximum Wall locus gradient, angle, cohesion and angle at a given stress, fill bulk density and maximum bulk density.

- **Bulk Density Test data sets:**
  Statistics can be done the fill bulk density and the maximum bulk density.
Appendix A: OVERVIEW OF POWDER FLOW PROPERTIES

Problems with Powder that relate to Gravity Flow Behavior

A typical industrial powder processing line will include several storage vessels (e.g. bins, bunkers, silos, hoppers, Intermediate Bulk Containers or IBCs, sacks etc), feeding or handling steps (e.g. belt conveyor, screw conveyor, pneumatic conveyor, gravity chutes etc) and processing steps (e.g. milling, mixing, drying, bagging etc). A major industrial problem is getting the powder to discharge reliably from storage into the next process step. Therefore to understand the application of powder flow measurements, it is useful to have some background knowledge of the flow patterns and flow obstructions that can occur inside the storage vessels on a processing line.

What are the powder flow patterns that can occur in a process storage vessel?

Principally there are two different flow patterns that can occur:

Core-flow (shown in Figure A-1a) can be considered the default flow pattern and is characterized by powder discharge through a preferential flow channel above the draw down point of the outlet. Powder is drawn into the flow channel from the top free surface of the inventory. This gives a first-in last-out discharge regime and, if operated on a continuous (rather than batch) mode, the powder around walls in the lower section will remain static in the vessel until the time that it is drained down to empty.

Mass-flow (shown in Figure A-1b) is the desirable flow pattern for powders that are poor flowing or time sensitive, but must be specifically designed for. Here the entire contents of the vessel are ‘live’, giving a first-in first-out discharge regime. To achieve this, the hopper walls must be sufficiently steep and smooth. For a given wall material/converging angle, the powder wall friction must be below a critical value. Also, the product discharge must be controlled by a valve or feeder that allows powder to flow through the entire cross sectional area of the outlet. (It is this final point that prevents many vessels from operating in mass-flow.)

A wall friction test will be able to give an approximate assessment of whether a given hopper geometry will support mass-flow (with the proviso that the outlet area is fully active). For an exact calculation of the maximum mass-flow hopper half angle, both wall friction and flow function tests must be undertaken.

What are the powder obstructions that can occur to prevent flow?

Principally there are two different flow obstructions that can occur:

‘Rat-holing’ (shown in Figure A-2a) is the principle flow obstruction in a core-flow vessel and is where the powder in the flow-channel above the outlet discharges leaving a stable internal structure.

‘Arching’ (shown in Figure A-2b) is the flow obstruction in a mass-flow vessel, where a stable powder arch forms across the outlet or converging walls of the hopper, thereby preventing flow.

For a given powder there is a critical outlet dimension that must be exceeded to ensure reliable discharge of a core-flow or mass-flow vessel. These are the critical rat-hole diameter Drh and the critical arching diameter Dc or Dp (depending on the hopper geometry). The Brookfield Powder Flow Flow Tester (PFT) can calculate these critical dimensions following a flow function
measurement. An accurate dimension requires a wall friction test as well. Note that for a given powder the rat-hole diameter is significantly larger than the arching diameter.

**What are the flow patterns that can occur?**

![Figure A-1a: Core-flow](image1)

![Figure A-1b: Mass-flow](image2)

**What are the forms of the flow obstructions?**

\[
D_{RH} = \frac{2 \times \sigma_c \times 1000}{\rho_B \times g}
\]

**Figure A-2a: 'Rat-hole'**

\[
D_{c} = \frac{2 \times \sigma_c \times 1000}{\rho_B \times g}
\]

**Conical hopper:**

\[
D_{c} = \frac{2 \times \sigma_c \times 1000}{\rho_B \times g}
\]

\[
(\text{Where } 3Dp < L)
\]

**Figure A-2b: Arch**

**Figure A-3a: Conical hopper**

**Figure A-3b: Wedge (plane) hopper**
Note: Two types of hopper shape are considered: conical hoppers and wedge (or plane) hoppers as shown in Figure A-3a & A-3b.

Key differences between powders and fluids

For Newtonian fluids the resistance to shear (viscosity) is independent of the normal pressure but dependent on the shear rate. In powders the effect of these factors is reversed so that shear stress of a powder is strongly dependent on the normal stress but independent of the shear rate. Hence when characterizing powders, test are undertaken at a single speed but over a range of normal stresses. The other key difference is that powders are anisotropic so the stresses are not equal in all directions and are frictional so that they can generate shear stresses at wall boundaries (see wall friction section).

Flow function test

The primary measure of powder flowability is the powder flow function – which gives a measure of the amount of strength the material retains at a stress free surface following consolidation to a given stress level. The simplest way of explaining the flow function is with the uniaxial unconfined failure test shown in Figure A-4, which measures the strength of a free standing column of powder. This condition is analogous to the condition of the powder arch across a hopper outlet shown in Figure A-2b.

i) Consolidation of sample. Powder is placed in a cylindrical cell and compacted under a known normal stress $\sigma_1$.

ii) Unconfined sample. The mould is now carefully removed to reveal a compacted column of powder.

iii) Unconfined failure of sample. The normal stress acting on the column of powder is gradually increased until failure occurs, and the peak normal stress $\sigma_c$ is recorded.

\[
\sigma_1 \quad \sigma_3 = 0
\]

*Figure A-4: Uniaxial unconfined failure test*

The above uniaxial unconfined failure test is conducted over a range of consolidation stresses and the flow function is constructed by plotting the unconfined failure strength versus the consolidation stress as shown in Figure A-5. The greater the flow factor (ff) value, the more free-flowing the powder.
The standard classification of powder flowability is as follows:

- \( ff < 1 \) Non flowing
- \( 1 < ff < 2 \) Very cohesive
- \( 2 < ff < 4 \) Cohesive
- \( 4 < ff < 10 \) Easy flowing
- \( 10 < ff \) Free flowing

**Anticipated uses of the Brookfield Powder Flow Tester:**

- **Bench marking** - Measure flow properties on all raw powders and blends to determine if there are differences in their flow-ability and whether these corresponded with plant experience.

- **New materials** - Test new ingredients/blends versus existing ingredients /blends to determine whether the alternative material is likely to be easier, more difficult or no different to handle. This potential material handling cost can be factored into the purchasing decision.

- **Reverse engineering** - If you have plant experience with powders that flow easily or poorly on a given process line, you can use the PFT to determine the flow properties of each powder and determine over time a flowability window required for flow on a given line.

- **Design** - Design the geometry (converging angle and outlet size) of new hoppers/silos for reliable flow.

**Alternative methods of displaying the flow function test results**

To demonstrate powder flow-ability, the flow function can be presented graphically (as in Figure A-5) to describe behavior over the stress range of approximately 0.6kPa to 10kPa. This stress range is representative of that experienced by the powder in small to intermediate sized silos. However, describing flowability with a function may complicate the analysis as it is sometimes found that the flow functions of two different materials cross over one another, so that their
relative ranking changes with stress levels. Alternatively, flowability rankings for specific stress levels can be determined by calculating the following parameters:

- **Estimated Critical Arching diameter [m]:** The minimum silo outlet size for reliable gravity discharge in mass-flow, calculated using the arching equation in Figure A-2b. The stress value is the intercept of the flow function with an ff = 1.4 line*.

- **Estimated Critical ‘Rat-hole’ diameter in [m]:** The minimum outlet diameter to prevent the formation of a stable ‘rat-hole’ in a core-flow vessel. The outlet diameter is calculated using the rat-holing equation in Figure A-2a. The stress value is the intercept of the flow function with an ff = 2.5 line**.

- **Flow index:** The gradient of a line from the origin to the last point on the flow function (by default**), typically in the range of 0.1 to 1.0. This index will give a comparison of materials behavior at intermediate compaction stresses greater than one meter depth of powder.

- **Flow intercept:** The intercept of the best fit linear failure function with the unconfined failure strength axis giving a number in kPa. This gives a number that reflects the powders flowability at compaction stresses typically less than 0.15m depth of powder.

*Note:* A time consolidated flow function test allows the user to investigate whether the material gains strength during long term storage.

* These are the default flow factor settings but they can be adjusted by the user within a 1.0 to 10.0 range for silo design applications.

** Can be user set to any stress level.

**Wall friction test**

The friction acting at the wall/powder interface has a significant influence on the stress distribution within processing vessels, silos and hoppers.

The higher the wall friction, the more of the powder weight is transferred down through the silo/vessel/container walls, rather than compacting the bulk solid below. The lower the friction, the more the self-weight is transmitted through the bulk solid. This ‘Jassen effect’ is illustrated in Figure A-6, which demonstrates how the vertical pressures in the vertical section of a silo would vary if the wall friction were increased from zero to a large value of 40°. The presence of the wall friction has a negative feed-back effect on the pressure increase with depth, so generally the stresses approach constant values at a depth of approximately 4 vessel diameters.
Software can be used to estimate pressures in a container based on measurements of the bulk density $\rho$, wall friction $\phi_w$, internal friction $\delta$, and container diameter $D$. The principal consolidation pressure $\sigma_1$ at depth $Z$ is given by the following equation.

$$\sigma_1 = \frac{\rho \cdot g \cdot D}{4 \cdot \lambda \cdot \tan \phi_w} \left( 1 - e^{-\frac{4 \cdot \lambda \cdot \tan \phi_w \cdot Z}{D}} \right)$$

Where: $\lambda = \frac{1 - \sin \delta_j}{1 + \sin \delta_j}$

The wall friction angle represents the angle to which a wall surface must be inclined as shown in Figure A-7 to cause powder to slip. The wall friction angle is typically in the range of 10 to 45 degrees.

The wall friction angle is also called the chute angle.

**Figure A-6: Stress distributions in vertical walled vessels**

**Figure A-7: Wall friction**
Outputs of the wall friction test

While the results of the wall friction test can be displayed graphically in the form of a wall failure locus as shown in Figure A-8a (representing the limiting shear stress the powder can support at a wall), or the form of a wall friction angle function as shown in Figure A-8b (representing how the wall friction angle changes with reducing stress), one of the following four flow indices derived from the maximum wall friction locus are usually adequate. These wall failure properties are:

- $\theta_c$, $\theta_p$ The maximum mass-flow hopper half angle (measured to the vertical) for conical or planar hoppers.
- $\phi_w$ The maximum wall friction angle to determine the minimum chute angle for gravity flow (see Figure A-8b).
- $\text{Grad}$ The maximum wall friction angle displayed as a coefficient.
- $c_w$ The wall cohesion shear stress in kPa that can be supported at the wall under zero normal stress (see Figure 8a). This determines the ‘stickiness’, i.e. whether powder is likely to stick to wall surface under close to zero stress. i.e. will powder build up on the walls of the chutes around discharge/transfer points.

An extended wall friction test allows the wall sample to be subject to large shear displacements (on the order of 30 meters) to establish whether long term powder build up on the wall would be expected.

Bulk density test

It is the self-weight of the powder, its bulk density, that controls the stresses acting on the powder when flowing or when static in processing lines/ silos etc. The bulk density is measured during the course of the flow function test (and is required to calculate the critical outlet dimensions) and the wall friction test, but it can also be measured in a separate single test for bulk density alone.

Compacted bulk density ($\rho_{\text{comp}}$)
The bulk density is commonly displayed as a bulk density curve (Figure A-9). Generally a free flowing material will be incompressible - so will show only a small increase in density with stress. A very cohesive poorly flowing bulk solid by comparison will show a large increase in bulk density with increasing stress.

\( \rho_{\text{fill}} \) The fill bulk density to expected when the powder is poured into a container

\( \rho_{\text{comp}} \) The compacted bulk density will give an indication of the bulk density to expect if the material is poured and compacted to high stress.

**Summary**

To summarize, the Brookfield Powder Flow Tester offers four standard tests,

1. **Flow function test** - Measures internal strength, flow function, internal friction function and bulk density function - used for characterizing the flow strength and arching/rat-holing potential of powders.
2. **Time consolidated flow function test** – Same as above but following static storage for a user defined time period.
3. **Wall friction test** - Measures friction between the powder and a given wall surface and the bulk density function – used for assessing mass-flow hopper half angles and gravity flow chute angles.
4. **Bulk density test** – Measures bulk density curve of the powder.

**Note:** To undertake a full silo design requires the user to run and combine the results of tests 1, 2 and 3.