

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

Characterization and Flow of Food and Mineral Powders

**A thesis presented in partial fulfillment of the
requirements for the degree of**

**Doctor of Philosophy
in
Engineering**

**at Massey University, Manawatū,
New Zealand.**

Horng Yuan Saw

2016

Abstract

Powders are important commodities across different industries, such as the food and pharmaceutical industries. In these industries, powders are usually made, mixed, milled, packaged, and stored; these operations require the powders to move and flow under desired conditions and different stress levels. Failure to flow will cause hindrances to production; therefore knowledge of powder flow or flowability is important. There is a constant demand for accurate, reliable, and robust measurement and characterization methods for powder flowability.

Powders behave differently under varying conditions; the behaviour of a powder is influenced by particle size distribution, and powder handling and processing conditions. There is to date no one “standard” method to characterize powder flowability; it is common to use a variety of methods and devices to measure flow properties and provide insight into the behaviour and flow characteristics of powders under different conditions.

The flow properties of model food and mineral powders were measured and assessed by shear testing, compression via tapping, fluidization, and powder tumbling. Shear testing was done with an annular shear cell following Jenike (1964) and Berry, Bradley and McGregor (2014). Compression via tapping was performed according to a procedure in the dairy industry (Niro, 1978) and the European Pharmacopoeia (Schüssele & Bauer-Brandl, 2003). Fluidization was used to measure powder bed expansion and bed collapse following the powder classification framework provided by Geldart and co-workers (Geldart, 1973; Geldart, Harnby, & Wong, 1984; Geldart & Wong, 1984, 1985). Powder tumbling was performed in a novel *Gravitational Displacement Rheometer*, GDR, which measured the motion and avalanche activity of powders that moved under their own weight when rotated in a cylinder at different drum speed levels. The flow data from each characterization method were evaluated individually with regards to particle size distribution and then assessed collectively. The findings presented and discussed include the i) demonstration of the dominant influence of surface-volume mean particle diameter on powder flow properties, ii) characterization of flowability based on Jenike’s arbitrary flow divisions, iii) development of new correlations for the estimation of powder cohesion and bulk density at low preconsolidation stresses, iv) demonstration of hopper outlet diameter as a measure of flowability, v) demonstration of the limited utility of Hausner ratio as a flowability index, vi) substantiation of von Neumann ratio as a sensitive and useful indicator for identifying the onset of bubbling in fluidized beds using bed pressure fluctuation data, and vii) demonstration of the utility of standard deviation of the GDR load cell signal as an indicator of powder avalanche activity. These findings provide improved understanding and knowledge of powder flowability; they can be used to assist and facilitate the development of new techniques and solutions relevant to the handling and processing of powders especially in the food and pharmaceutical industries.

Acknowledgement

I thank and praise my Lord and Saviour Jesus Christ for making everything possible.

My heartfelt acknowledgment and gratitude go to the people listed below; they have made various contributions to the completion of this Ph.D. thesis:

Ruth Saw, my beloved wife, soul mate, and best friend, my beloved mother Madam Yoke Yee Hor, and sisters Pek Wan Saw and Pek En Saw.

Professor Clive E. Davies, Principal Supervisor, and Professor Anthony H. J. Paterson and Professor Jim R. Jones, Co-supervisors, School of Engineering and Advanced Technology, Massey University.

Ann-Marie Jackson, John Edwards, Clive Bardell, Nick Look, Anthony Wade, and Kerry Griffiths, technical services staff of School of Engineering and Advanced Technology, Massey University.

Michele Wagner, Linda Lowe, Glenda Rosoman, Gayle Leader, Trish O'Grady, and Dilantha Punchihewa, administrative staff of School of Engineering and Advanced Technology, Massey University.

Professor Paul J. Moughan, Professor Harjinder Singh, John Henley-King, Dr. Guillaume Brisson, Dr. Emile S. Webster, and Janiene Gilliland of Riddet Institute.

Professor Fernando J. Muzzio of Rutgers University, Associate Professor Tony Howes of the University of Queensland, Dr. Kalyana Pingali and Casey Kick of Western Michigan University, and Dr. Abraham S. Chawanji of Fonterra Research Centre.

Pastors Dale and Rachel Meacheam, Pastor Nick Ling, friends from Vision Church Palmerston North, and Pastor Lionel Smith.

Pastor Ezra Chin and friends from Emmanuel Church Kota Kinabalu, Malaysia.

Table of Content

	Page
Abstract	i
Acknowledgement	ii
Table of Content	iii
List of Figures	ix
List of Tables	xv
Nomenclature	xvi
Chapter 1 – Introduction	1
1.1 Background	1
1.2 Thesis Structure	2
Chapter 2 – Preparation of Model Powders and Characterization of Physical Properties	3
2.1 Introduction	3
2.2 Literature Review	3
2.2.1 Particle size distribution and mean particle diameter	3
2.2.2 Fines fraction	5
2.2.3 Particle shape	6
2.2.4 Influence of particle size distribution, mean particle diameter, and fines fraction on powder behaviour	6
2.2.5 Summary of literature review	7
2.3 Aims	7
2.4 Materials, Methods and Analysis	7
2.4.1 Materials and preparation of model powders	7
2.4.2 Measurement of particle size distribution, diameters d_{10} , d_{50} , d_{90} , and span of size distribution	8
2.4.3 Determination of surface-volume mean particle diameters $d_{32,M}$, d^*_{32} , and $d_{32,S}$	9
2.4.4 Determination of fines fraction F_{10} , F_{20} , F_{30} , F_{38} , and F_{45}	9
2.4.5 Examination of particle shape	9
2.5 Results	9
2.5.1 Particle size distribution, span of size distribution, diameters $d_{32,M}$, d^*_{32} , and $d_{32,S}$, and fines fraction of model powders	9
2.5.2 Particle shape of model powders	12
2.5.3 Relationships between d^*_{32} , span of particle size distribution, and fines	16

fraction		
2.6	Discussion	17
2.7	Conclusions	19
 Chapter 3 – Powder Shear Testing		 20
3.1	Introduction	20
3.2	Literature Review	20
3.2.1	Yield locus, major consolidation and unconfined yield stresses, and effective angle of internal friction	21
3.2.2	Powder flow function and numerical characterization of powder flowability	24
3.2.3	Cohesion	26
3.2.4	Bulk density under consolidation	27
3.2.5	Minimum width of hopper outlet for mass flow	30
3.2.6	Summary of literature review	32
3.3	Aims	33
3.4	Materials, Methods and Analysis	33
3.4.1	Materials	33
3.4.2	Measurement of yield locus, powder flow function, effective angle of internal friction and bulk density	33
3.4.3	Measurement of kinematic angle of wall friction	34
3.4.4	Analysis	34
3.4.4.1	Powder flow function and Jenike's arbitrary powder flow divisions	34
3.4.4.2	Cohesion	34
3.4.4.3	Bulk density under consolidation	36
3.4.4.4	Hopper outlet <i>B</i>	36
3.5	Results	36
3.5.1	Yield locus	36
3.5.2	Powder flow function	37
3.5.3	Cohesion	38
3.5.4	Bulk density under consolidation	43
3.5.5	Hopper outlet <i>B</i>	50
3.6	Discussion	52
3.6.1	Yield locus and powder flow function	52
3.6.2	Cohesion and Equation 3.21	53
3.6.3	Consolidated bulk density, bulk density correlations, and Equation 3.28	55

3.6.4	Simultaneous use of Equations 3.21, 3.28, and 3.30	56
3.6.5	Hopper outlet <i>B</i>	56
3.6.6	Effects of room temperature and relative humidity	57
3.7	Conclusions	58
Chapter 4 – Powder Compression via Tapping		60
4.1	Introduction	60
4.2	Literature Review	60
4.2.1	Loose poured bulk density and tapped density	60
4.2.2	Tapped density profiles, Hausner ratio, and powder compression correlations	62
4.2.3	Hausner ratio in powder flow indication and general powder classifications	64
4.2.4	Summary of literature review	67
4.3	Aims	67
4.4	Materials, Methods and Analysis	68
4.4.1	Materials	68
4.4.2	Measurement of loose poured bulk density	68
4.4.3	Measurement of tapped density	68
4.4.4	Measurement of flow properties with an annular shear cell	69
4.4.5	Analysis	69
4.5	Results	70
4.5.1	Loose poured bulk density	70
4.5.2	Tapped density and powder compression correlations	72
4.5.3	Hausner ratio	76
4.6	Discussion	80
4.6.1	Loose poured bulk density and tapped density	80
4.6.2	Fitting parameters a_t , b_t , $k_{t,M1}$ and $k_{t,M2}$	81
4.6.3	Estimation of loose poured bulk density with Equation 4.1 and Equation 4.2	84
4.6.4	Hausner ratio, cohesion, and the ratio of major consolidation stress and unconfined yield stress	86
4.7	Conclusions	90
Chapter 5 – Gas-Fluidization		91
5.1	Introduction	91
5.2	Literature Review	91

5.2.1	Gas-fluidization phenomenon	91
5.2.2	Powder bed expansion	93
5.2.2.1	Geldart Group A powders	93
5.2.2.2	Geldart Group B powders	93
5.2.2.3	Geldart Group C powders	94
5.2.2.4	Geldart Group D powders	96
5.2.2.5	Geldart C/A, A/B, and B/D boundary powders	96
5.2.3	Pressure fluctuations and transitions in fluidized beds	97
5.2.4	Powder bed collapse	98
5.2.4.1	Bed collapse curves for Geldart Groups of powders	98
5.2.4.2	Type of bed collapse system	99
5.2.4.3	Standardized collapse time	101
5.2.5	Fluidization, powder characterization and other flowability characterization methods	102
5.2.6	Summary of literature review	103
5.3	Aims	103
5.4	Materials, Methods and Analysis	104
5.4.1	Materials	104
5.4.2	Experimental setup	104
5.4.3	Measurement of bed pressure drop, bed height, and onset of bubbling	105
5.4.4	Measurement of bed collapse	105
5.4.5	Analysis	106
5.4.5.1	Transition velocities and regimes in fluidization	106
5.4.5.2	Bed collapse	106
5.5	Results	107
5.5.1	Transition velocities	107
5.5.2	Fluidization behaviour and pressure fluctuations	109
5.5.3	Bed collapse	116
5.6	Discussion	118
5.6.1	Superficial velocities, transitions and pressure fluctuations in fluidized beds	118
5.6.2	Powder bed collapse, standardized collapse time and cohesion	119
5.6.3	Geldart Powder Groups and Hausner ratio at 1,250 taps	119
5.7	Conclusions	120
	Chapter 6 – Powder Tumbling	121
6.1	Introduction	121

6.2	Literature Review	121
6.2.1	Flow regimes of powders in rotating drums	121
6.2.2	Characterizing powder flowability with a rotating disc	123
6.2.3	Modification of the rotating disc apparatus	123
6.2.4	Significant findings on powder flowability with rotating drum apparatuses	124
6.2.4.1	Identification of flow regimes and regime transitions	124
6.2.4.2	Identification of behaviour of Geldart Powder Groups	125
6.2.4.3	Flow Index as indicator for cohesivity and flowability	125
6.2.4.4	Powder dilation as indicator for cohesivity and flowability	127
6.2.5	Summary of literature review	128
6.3	Aims	128
6.4	Materials, Methods and Analysis	129
6.4.1	Materials	129
6.4.2	Experimental setup	129
6.4.3	Setup and operation of GDR	130
6.4.4	Analysis	131
6.5	Results	131
6.5.1	Effect of drum fill level on avalanche activity	131
6.5.2	Avalanche activity and Geldart Powder Classification	133
6.5.3	Avalanche activity and d^*_{32}	134
6.6	Discussion	136
6.6.1	Avalanche activity and influence of drum fill level	136
6.6.2	Avalanche activity and Geldart Groups C, A, A/B and B powders	137
6.6.3	Avalanche activity, Flow Index and $1/d^*_{32}$	139
6.6.4	Avalanche activity and powder dilation	140
6.7	Conclusions	140
Chapter 7 – Summary		142
7.1	Characterization	142
7.2	Cohesion	142
7.3	Bulk density	143
7.4	Flowability	143
7.5	Compressibility	143
7.6	Fluidization	144
7.7	Tumbling	144

References	146
Appendix 1.1	153
Appendix 2.1	156
Appendix 2.2	157
Appendix 3.1	161
Appendix 3.2	163
Appendix 3.3	167
Appendix 3.4	168
Appendix 3.5	169
Appendix 3.6	170
Appendix 3.7	171
Appendix 3.8	172
Appendix 3.9	174
Appendix 4.1	176
Appendix 4.2	177
Appendix 4.3	178
Appendix 4.4	179
Appendix 4.5	181
Appendix 5.1	183
Appendix 5.2	185
Appendix 5.3	186
Appendix 5.4	187
Appendix 5.5	192
Appendix 6.1	198
Appendix 6.2	204

List of Figures

Figure	Caption	Page
2.1	An example of particle size distribution with real data; plot of volume percentage versus incremental mean particle diameter	4
2.2	An example of particle size distribution with real data; plot of cumulative volume fraction versus incremental mean particle diameter	4
2.3	Particle size distribution of milled lactose LP4; plot of volume percentage versus incremental mean particle diameter	10
2.4	Particle size distribution of milled lactose LP4; plot of cumulative volume fraction versus incremental mean particle diameter	10
2.5	Particle shape of milled lactose powder LP1	13
2.6	Particle shape of milled lactose powder LP4	13
2.7	Particle shape of milled lactose powder LM1	14
2.8	Particle shape of spray-dried lactose powder LT1	15
2.9	Particle shape of sand S1	15
2.10	Particle shape of refractory dust RD1	16
2.11	Plot of d^*_{32} versus span of particle size distribution	17
2.12	Plot of d^*_{32} versus F_{45}	17
2.13	Plot of $1/d^*_{32}$ versus fines fraction for milled lactose powders	17
2.14	Plot of d^*_{32} versus $d_{32,M}$	18
3.1	Plot of shear stress versus consolidation stress with a yield locus, two Mohr circles, and the effective yield locus	21
3.2	Arching in the gravity flow of a powder from a hopper, adapted from Rhodes (1998)	23
3.3	Examples of powder flow functions with real data and Jenike's criteria for powder flowability	25
3.4	Determination of critical stress developed in an arch surface with powder flow function and hopper flow factor	32
3.5	Plot of shear stress versus normal stress at a preconsolidation stress of 1.2 kPa for milled lactose LP4, LM1, LM2, LP1, and LP3, sand S1, and refractory dust RD1 with d^*_{32} ranging from ~23–223 μm	37
3.6	Powder flow functions of 13 milled lactose powders and Jenike's arbitrary powder flow divisions	38
3.7	Powder flow functions of spray-dried lactose LT1 and LT2, sand S1, S2 and S3, refractory dust RD1, RD2 and RD3, and Jenike's arbitrary powder flow divisions	38

3.8	Plot of C versus σ_{pre} ; milled lactose LP4 is <i>very cohesive</i> and LM7, LM8, LM1, and LM9 are <i>cohesive</i> at $\sigma_{\text{pre}}=1.2$ kPa	39
3.9	Plot of C versus σ_{pre} ; milled lactose LM4, LP2, and LM2 are <i>easy flowing</i> at $\sigma_{\text{pre}}=1.2$ kPa	39
3.10	Plot of C versus σ_{pre} ; milled lactose LM3, LM5, LP1, LM6, and LP3 are <i>free flowing</i> at $\sigma_{\text{pre}}=1.2$ kPa	40
3.11	Plot of C versus σ_{pre} for spray-dried lactose LT1 and LT2, sand S1, S2 and S3, and refractory dust RD1, RD2 and RD3	40
3.12	Plot of cohesion at zero preconsolidation stress, C_0 versus d^*_{32}	40
3.13	Plot of cohesion at zero preconsolidation stress, C_0 versus $\rho_0/(\rho_p d^*_{32})$	40
3.14	Plot of C versus $\rho_B/(\rho_p d^*_{32})$ for milled lactose powders	41
3.15	Plot of C versus $\rho_B/(\rho_p d^*_{32})$ for spray-dried lactose powders	41
3.16	Plot of C versus $\rho_B/(\rho_p d^*_{32})$ for sand	42
3.17	Plot of C versus $\rho_B/(\rho_p d^*_{32})$ for refractory dust	42
3.18	Plot of C versus $\rho_B/(\rho_p d^*_{32})(\sigma_{\text{pre}}/\sigma_{\text{pre,min}})^{0.3}$ for milled lactose powders; σ_{pre} is from 0.31–4.85 kPa	43
3.19	Plot of C versus $\rho_B/(\rho_p d^*_{32})(\sigma_{\text{pre}}/\sigma_{\text{pre,min}})^{0.3}$ for spray-dried lactose powders; σ_{pre} is from 0.31–2.41 kPa	43
3.20	Plot of C versus $\rho_B/(\rho_p d^*_{32})(\sigma_{\text{pre}}/\sigma_{\text{pre,min}})^{0.3}$ for sand; σ_{pre} is from 0.31–1.20 kPa	43
3.21	Plot of C versus $\rho_B/(\rho_p d^*_{32})(\sigma_{\text{pre}}/\sigma_{\text{pre,min}})^{0.3}$ for refractory dust; σ_{pre} is from 0.31–2.41 kPa	43
3.22	Plot of consolidated bulk density versus preconsolidation stress for powders RD1, LP4, S1, LM9, LM1, and LP1	44
3.23	Plot of $(\rho_B-\rho_0)/\rho_0$ versus $\log \sigma_{\text{pre}}$ for Equation 3.6	45
3.24	Plot of $\rho_B \sigma_{\text{pre}}/(\rho_B-\rho_0)$ versus σ_{pre} for Equation 3.9	45
3.25	Plot of $\ln [\ln(\rho_B/\rho_0)]$ versus $\ln \sigma_{\text{pre}}$ for Equation 3.11	45
3.26	Plot of $\log (\rho_B/\rho_0)$ versus $\log \sigma_{\text{pre}}$ for Equation 3.13	45
3.27	Plot of $\log (\rho_B-\rho_0)$ versus $\log \sigma_{\text{pre}}$ for Equation 3.15	46
3.28	Plot of $k_{s,M1}$ of Equation 3.6 versus $1/d^*_{32}$	46
3.29	Plot of $k_{s,M2}$ of Equation 3.6 versus $1/d^*_{32}$	46
3.30	Plot of a_s of Equation 3.8 versus $1/d^*_{32}$	47
3.31	Plot of k_{N1} of Equation 3.10 versus $1/d^*_{32}$	47
3.32	Plot of k_{J2} of Equation 3.12 versus $1/d^*_{32}$	47
3.33	Plot of k_{G1} of Equation 3.14 versus $1/d^*_{32}$	47
3.34	Plot of b_s of Equation 3.8 versus $1/d^*_{32}$	48
3.35	Plot of k_{N2} of Equation 3.10 versus $1/d^*_{32}$	48

3.36	Plot of k_{J1} of Equation 3.12 versus $1/d^*_{32}$	48
3.37	Plot of k_{G2} of Equation 3.14 versus $1/d^*_{32}$	48
3.38	Plot of $k_{s,M1}$ and $k_{s,M2}$ of Equation 3.6 versus $1/d^*_{32}$ for milled lactose powders	49
3.39	Plot of ρ_0 versus $1/d^*_{32}$ for milled lactose powders	49
3.40	Plot of $(\rho^*_B - \rho_B)/\rho_B$ versus ρ_B for milled lactose powders; ρ^*_B is estimated with Equation 3.28	50
3.41	Plot of ρ_0 versus $1/d^*_{32}$ for spray-dried lactose powders, sand, and refractory dust	50
3.42	Plot of σ_y or σ_D versus σ_c for LP4	51
3.43	Plot of σ_y or σ_D versus σ_c for LM6	51
3.44	Plot of $(\rho^*_B - \rho_B)/\rho_B$ versus ρ_B for milled lactose powders; ρ^*_B is estimated with Equation 3.29	52
3.45	Plot of hopper outlet B versus $1/d^*_{32}$ for milled lactose powders	52
3.46	Plot of $(C^* - C)/C$ versus C for milled lactose powders; C^* is calculated with Equation 3.21 and measured ρ_B values	53
3.47	Plot of C versus $1/d^*_{32}$ for milled lactose powders that are <i>easy flowing</i> and <i>free flowing</i> at $\sigma_{pre}=1.2$ kPa	54
3.48	Plot of B versus σ_c/σ_y at $\sigma_{pre}=1.2$ kPa for milled lactose powders	57
4.1	Plot of loose poured bulk density measured by modified NZS3111 method versus $1/d^*_{32}$	72
4.2	Tapped density profiles of powders LP4, LP3, S1, and RD1	73
4.3	Plot of tapped density at 1250 taps versus $1/d^*_{32}$	73
4.4	Plot of $m_{tap}N/(m_{tap}-m_0)$ versus N	74
4.5	Plot of $(m_{tap}-m_0)/m_0$ versus $\log N$	74
4.6	Plot of parameter a_t versus d_{50}	75
4.7	Plot of parameter b_t versus d_{50}	75
4.8	Plot of parameter a_t versus $1/d^*_{32}$	76
4.9	Plot of parameter b_t versus $1/d^*_{32}$	76
4.10	Plot of parameter $k_{t,M1}$ versus $1/d^*_{32}$	76
4.11	Plot of parameter $k_{t,M2}$ versus $1/d^*_{32}$	76
4.12	Plot of Hausner ratio at 1250 taps versus $1/d^*_{32}$	77
4.13	Plot of cohesion at $\sigma_{pre}=1.20$ kPa versus Hausner ratio at 1250 taps	78
4.14	Plot of parameter k_{C1} versus $\log \sigma_{pre}$	79
4.15	Plot of parameter k_{C2} versus $\log \sigma_{pre}$	79
4.16	Ratio σ_c/σ_y at $\sigma_{pre}=1.20$ kPa versus Hausner ratio at 1250 taps	79
4.17	Plot of parameter k_{F1} versus σ_{pre}^2	80

4.18	Plot of parameter k_{F2} versus σ_{pre}	80
4.19	Plot of a_t versus $1-(1/H_{R,1250})$	82
4.20	Plot of a_t versus a_s of Equation 3.8	82
4.21	Plot of b_t versus b_s of Equation 3.8	83
4.22	Plot of $k_{t,M1}$ versus $k_{s,M1}$ of Equation 3.6	84
4.23	Plot of $k_{t,M2}$ versus $k_{s,M2}$ of Equation 3.6	84
4.24	Plot of $(\rho^*_{0,1}-\rho_{0,mNZS3111})/\rho_{0,mNZS3111}$ versus $\rho_{0,mNZS3111}$	85
4.25	Plot of $(\rho^*_{0,2}-\rho_{0,mNZS3111})/\rho_{0,mNZS3111}$ versus $\rho_{0,mNZS3111}$	85
4.26	Plot of $(\rho^*_{0,3}-\rho_{0,mNZS3111})/\rho_{0,mNZS3111}$ versus $\rho_{0,mNZS3111}$	85
4.27	Plot of $(H^*_{R,1250}-H_{R,1250})/H_{R,1250}$ versus $H_{R,1250}$	86
4.28	Plot of $(C^*-C)/C$ versus C for lactose LP4 that is <i>very cohesive</i> at $\sigma_{\text{pre}}=1.2$ kPa	87
4.29	Plot of $(C^*-C)/C$ versus C for powders that are <i>cohesive</i> at $\sigma_{\text{pre}}=1.2$ kPa	87
4.30	Plot of $(C^*-C)/C$ versus C for powders that are <i>easy flowing</i> at $\sigma_{\text{pre}}=1.2$ kPa	88
4.31	Plot of $(C^*-C)/C$ versus C for powders that are <i>free flowing</i> at $\sigma_{\text{pre}}=1.2$ kPa	88
4.32	Plot of $[(\sigma_c^*/\sigma_y^*)-(\sigma_c/\sigma_y)]/(\sigma_c/\sigma_y)$ versus σ_c/σ_y for lactose LP4 that is <i>very cohesive</i> at $\sigma_{\text{pre}}=1.2$ kPa	88
4.33	Plot of $[(\sigma_c^*/\sigma_y^*)-(\sigma_c/\sigma_y)]/(\sigma_c/\sigma_y)$ versus σ_c/σ_y for powders that are <i>cohesive</i> at $\sigma_{\text{pre}}=1.2$ kPa	88
4.34	Plot of $[(\sigma_c^*/\sigma_y^*)-(\sigma_c/\sigma_y)]/(\sigma_c/\sigma_y)$ versus σ_c/σ_y for powders that are <i>easy flowing</i> at $\sigma_{\text{pre}}=1.2$ kPa	89
4.35	Plot of $[(\sigma_c^*/\sigma_y^*)-(\sigma_c/\sigma_y)]/(\sigma_c/\sigma_y)$ versus σ_c/σ_y for powders that are <i>free flowing</i> at $\sigma_{\text{pre}}=1.2$ kPa	89
5.1	Three typical plots of bed pressure drop versus superficial gas velocity in the fluidization of powders, adapted from Richardson (1971)	92
5.2	Powder classification diagram for fluidization by air under ambient conditions (Geldart, 1973)	93
5.3	Bed collapse curves for Geldart (a) Group B, (b) Group A, and (c) Group C powders; adapted from Tung and Kwauk (1982) and Geldart and Wong (1985)	99
5.4	Schematic diagram of fluidized bed setup (not to scale)	104
5.5	Bed pressure fluctuations for lactose LP2 at U_{mf} , $U_{\text{mb},v}$, and U_{bv} for increasing gas flow	110
5.6	Plot of normalized bed parameters versus normalized superficial velocity, U/U_{mf} , for lactose LP2 and increasing U	111
5.7	Plot of normalized bed parameters versus normalized superficial velocity, U/U_{mf} , for lactose LP2 and decreasing U	111

5.8	Plots of σ and T^{-1} versus U for lactose LP2 and increasing U	112
5.9	Plots of σ and T^{-1} versus U for lactose LP2 and decreasing U	112
5.10	Plots of σ and T^{-1} versus U for lactose LP3 and increasing U	113
5.11	Plots of σ and T^{-1} versus U for lactose LP3 and decreasing U	113
5.12	Plot of normalized σ versus $U/U_{mb,v}$ for increasing U	114
5.13	Plot of normalized σ versus $U/U_{mb,v}$ for decreasing U	115
5.14	Plot of normalized T^{-1} versus $U/U_{mb,v}$ for increasing U	115
5.15	Plot of normalized T^{-1} versus $U/U_{mb,v}$ for decreasing U	116
5.16	Bed collapse profiles of refractory dust RD2 measured with single-drainage and double-drainage systems and at initial superficial velocity of $1.5U_{mb,v}$, $2U_{mb,v}$, and $3U_{mb,v}$	117
5.17	Plot of normalized bed height versus time for powders RD2, LM2, S2, LP2, LT2, LM3, LM6, and LP3	117
5.18	Plot of normalized bed height versus time for powders S3, LT1, S1, and RD1	117
5.19	Plot of t_c/H_{mf} against d^*_{32}	118
5.20	Plot of t_c/H_{mf} against C_0	118
6.1	Flow characteristics of fine and coarse powders in rotating drums by Huang et al. (2010); used with permission (see Appendix 6.1 for permission)	122
6.2	A photo of the Gravitational Displacement Rheometer	130
6.3	Plot of σ_{ws} against drum speed for lactose LP4 at 20–50% fill level	132
6.4	Plot of σ_{ws} against drum speed for sand S1 at 20–50% fill level	132
6.5	Plot of σ_{ws} against drum speed for refractory dust RD1 at 20–50% fill level	132
6.6	Plot of σ_{ws} against drum speed for lactose LM1 at 20–50% fill level	132
6.7	Plot of σ_{ws} against drum speed for lactose LP1 at 10–50% fill level	133
6.8	Plot of σ_{ws} against drum speed for glass beads B8 at 20–50% fill level	133
6.9	Plot of σ_{ws} against drum speed for Geldart Group A sand S1, refractory dust RD1, and lactose LM1 at 50% fill level	134
6.10	Plot of σ_{ws} against drum speed for Geldart Group C lactose LP4, Group A/B lactose LP1, and Group B glass beads B8 at 50% fill level	134
6.11	Plot of σ_{ws} at 5 RPM and 50% fill level against $1/d^*_{32}$	135
6.12	Plot of σ_{ws} at 10 RPM and 50% fill level against $1/d^*_{32}$	135
6.13	Plot of σ_{ws} at 15 RPM and 50% fill level against $1/d^*_{32}$	135
6.14	Plot of σ_{ws} at 20 RPM and 50% fill level against $1/d^*_{32}$	135
6.15	Plot of σ_{ws} at 25 RPM and 50% fill level against $1/d^*_{32}$	136
6.16	Plot of σ_{ws} at 30 RPM and 50% fill level against $1/d^*_{32}$	136
6.17	Tumbling bed profiles for Geldart Group A refractory dust RD1, sand S1	138

	and milled lactose LM1	
6.18	Tumbling bed profiles for Geldart Group C milled lactose LP4; there are three random shots at each drum speed	138
6.19	Tumbling bed profiles for Geldart Group A/B milled lactose LP1 and Group B glass beads B8	139
6.20	Plot of normalized bed height against time; bed collapse profiles for Geldart Group A sand S1 and refractory dust RD1	139
6.21	Plot of Flow Index, Equation 6.1, against $1/d^*_{32}$	140

List of Tables

Table	Caption	Page
2.1	Diameters d_{10} , d_{50} , d_{90} , $d_{32,M}$, d^*_{32} , $d_{32,S}$, and span $(d_{90}-d_{10})/d_{50}$ for milled and spray-dried lactose powders, sand, and refractory dust	11
2.2	Fines fraction F_{10} , F_{20} , F_{30} , F_{38} , and F_{45} for milled and spray-dried lactose powders, sand, and refractory dust	12
3.1	Jenike's limiting flow function values and arbitrary powder flow divisions (Jenike, 1964)	25
3.2	Values of δ_e , Φ_w , θ_p , σ_{crit} , $\rho^*_{B,crit}$, $H(\theta_p)$, and B for milled lactose powders	51
3.3	Estimated hopper outlet B for milled lactose powders and Jenike's arbitrary powder flow divisions (Jenike, 1964)	57
4.1	Loose poured bulk density and its standard deviation for milled and spray-dried lactose powders, sand, and refractory dust	71
4.2	Values of fitting parameters c_1 and c_2 , and R^2 for milled lactose and spray-dried lactose powders, sand, and refractory dust	77
5.1	Transition velocities of powders	108
6.1	Information on d^*_{32} , span, t_c/H_{mf} , C_0 , and Geldart Classification for lactose LP4, sand S1, refractory dust RD1, lactose LM1, lactose LP1, and glass beads B8	129

Nomenclature

A_p	Surface area of material [m^2]
a_s, b_s	Fitting parameters of Equations 3.8 and 3.9 [units according to usage]
a_t, b_t	Fitting parameters of Equations 4.1 [units according to usage]
B	Minimum width of outlet required for mass flow from a hopper [m]
C	Cohesion [Pa]
C^*	Estimated cohesion [Pa]
C_0	Cohesion at zero preconsolidation stress [Pa]
c_1, c_2	Fitting parameters of Equation 4.9 [units according to usage]
d_{pi}	Incremental mean particle diameter [m] which is the mean of the sum of upper and lower nominal apertures in sieve analysis
d_{10}	Particle diameter at 10% in a cumulative size distribution [m]
d_{32}	Surface-volume mean particle diameter [m]
$d_{32,M}$	Surface-volume mean particle diameter measured with Mastersizer 2000 [m]
$d_{32,S}$	Surface-volume mean particle diameter measured with sieve analysis [m]
d^{*32}	Surface-volume mean particle diameter calculated with Mastersizer data using bins equivalent to a full sieve analysis according to BS 410; powder in the range of 0–38 μm has been grouped together and assigned a mean particle diameter of 19 μm in the calculation [m]
d_{50}	Particle diameter at 50% in a cumulative size distribution [m]
d_{90}	Particle diameter at 90% in a cumulative size distribution [m]
FF	Powder flow function [-]
F_{10}	Fraction of fines smaller than 10 μm calculated with Mastersizer data [-]
F_{20}	Fraction of fines smaller than 20 μm calculated with Mastersizer data [-]
F_{30}	Fraction of fines smaller than 30 μm calculated with Mastersizer data [-]
F_{38}	Fraction of fines smaller than 38 μm calculated with Mastersizer data [-]
F_{45}	Fraction of fines smaller than 45 μm calculated with Mastersizer data [-]
ff	Jenike hopper flow factor [-]
g	Gravitational acceleration [m s^{-2}]
H	Powder bed height [m]
H_{mf}	Bed height at incipient fluidization [m]
H_R	Hausner ratio [-]
$H_{R,1250}$	Hausner ratio at 1250 taps [-]
$H^{*}_{R,1250}$	Hausner ratio estimated with Equation 4.9 and c_1 and c_2 values in Table 4.2 [-]
i	Label for data point [-]
k_1, k_2	Fitting parameters of Equation 3.7 [units according to usage]

k_{C1}, k_{C2}	Fitting parameters of Equation 4.10 [units according to usage]
k_{F1}, k_{F2}	Fitting parameters of Equation 4.15 [units according to usage]
k_{G1}, k_{G2}	Fitting parameters of Equations 3.14 and 3.15 [units according to usage]
k_{J1}, k_{J2}	Fitting parameters of Equations 3.12 and 3.13 [units according to usage]
k_{N1}, k_{N2}	Fitting parameters of Equations 3.10 and 3.11 [units according to usage]
$k_{s,M1}, k_{s,M2}$	Fitting parameters of Equation 3.6 [units according to usage]
$k_{t,M1}, k_{t,M2}$	Fitting parameters of Equation 4.2 [units according to usage]
m_0	Powder mass in the loose poured state [g]
m_{tap}	Powder mass after N^{th} taps [g]
N	Number of taps [-]
n (of Chapter 3)	Shear index of Warren-Spring equation [-]
n (of Chapter 5)	Number of data points [-]
n_1, n_2	Fitting parameters of Equation 4.5 [units according to usage]
P	Applied pressure [Pa]
T (of Chapter 3)	Powder tensile strength [Pa]
T^{-1} (of Chapter 5)	Inverse of von Neumann ratio, Equation 5.2 [-]
t_c	Time required for hindered settling, Equation 5.3 [s]
U	Superficial gas velocity [m s^{-1}]
U_{bv}	Minimum vigorous bubbling velocity [m s^{-1}]
U_{mb}	Minimum bubbling velocity [m s^{-1}]
$U_{\text{mb,v}}$	Experimental minimum bubbling velocity detected by visual inspection of bed surface [m s^{-1}]
$U_{\text{mb},\sigma}$	Minimum bubbling velocity estimated using the plot of $\sigma:U$ and determining U for $\sigma=0$ by extrapolation [m s^{-1}]
U_{mf}	Minimum fluidizing velocity [m s^{-1}]
V_B	Bulk volume of material [m^3]
V_{Initial}	Initial volume of powder bed in the GDR after the powder was shaken horizontally and vertically for an unreported fixed number of times and allowed to settle under its own weight [m^3]
V_{New}	Volume of powder in GDR measured at the first 11 revolutions [m^3]
V_p	Volume of material [m^3]
x (of Chapter 5)	Sample variable; bed pressure drop [Pa]
x_i (of Chapter 2)	Volume fraction of particles in i^{th} mean particle diameter range in sieve analysis [-]

Greek letters

ΔP_b	Bed pressure drop [Pa]
--------------	------------------------

ΔP_d	Distributor pressure drop [Pa]
Φ_w	Kinematic angle of wall friction [$^{\circ}$]
δ_e	Effective angle of internal friction [$^{\circ}$]
ε_{mb}	Bed voidage at bubbling onset [-]
ε_{mf}	Bed voidage at incipient fluidization [-]
μ (of Chapter 3)	Coefficient of friction [-]
μ (of Chapter 5)	Gas viscosity, Equation 5.3 [N s m $^{-2}$]
θ_a	Minimum angle for which avalanches are observed [$^{\circ}$]
θ_p	Semi-included angle of the conical section of a hopper [$^{\circ}$]
θ_s	Minimum angle which triggers powders to slip [$^{\circ}$]
ρ_0	Initial or loose poured bulk density [kg m $^{-3}$]
$\rho_{0,mNZS3111}$	Loose poured bulk density measured by the modified NZS3111 method [kg m $^{-3}$]
ρ_B	Bulk density [kg m $^{-3}$]
ρ_g	Gas density [kg m $^{-3}$]
ρ_p	Particle density [kg m $^{-3}$]
ρ_{tap}	Tapped density [kg m $^{-3}$]
$\rho^{*}_{0,1}$	Loose poured bulk density estimated with Equation 4.1 and a_t and b_t values in Appendix 4.1 [kg m $^{-3}$]
$\rho^{*}_{0,2}$	Loose poured bulk density estimated with Equation 4.1, a_t values in Appendix 4.1 and $b_t=0.0427$, the average value determined with the data of milled and spray-dried lactose powders, sand, and refractory dust [kg m $^{-3}$]
$\rho^{*}_{0,3}$	Loose poured bulk density estimated with Equation 4.2 and $k_{t,M1}$ and $k_{t,M2}$ values in Appendix 4.1 [kg m $^{-3}$]
σ (of Chapter 3)	Consolidation stress [Pa]
σ (of Chapter 5)	Standard deviation, Equation 5.1 [Pa]
σ_c	Major consolidation stress [Pa]
σ_{crit}	Critical stress developed in an arch surface [Pa]
σ^*_c/σ^*_y	Estimated ratio of major consolidation stress to unconfined yield stress [-]
σ_D	Major stress developed in a dome or pipe [Pa]
σ_{pre}	Preconsolidation stress [Pa]
$\sigma_{pre,min}$	Minimum preconsolidation stress [Pa]
σ_{ws}	Standard deviation of GDR drum weight shift [kg]
$\sigma_{ws,5RPM}$	Standard deviation of GDR drum weight shift at 5 RPM [kg]
$\sigma_{ws,10RPM}$	Standard deviation of GDR drum weight shift at 10 RPM [kg]
$\sigma_{ws,15RPM}$	Standard deviation of GDR drum weight shift at 15 RPM [kg]
$\sigma_{ws,20RPM}$	Standard deviation of GDR drum weight shift at 20 RPM [kg]
σ_y	Unconfined yield stress [Pa]

τ	Shear stress [Pa]
τ_{pre}	Constant shear stress at preshear [Pa]
τ_{ss}	Steady-state shear stress [Pa]
ω	Angular velocity [rad s^{-1}]