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5 **On the Design of Conical Hoppers for Spent Coffee Grounds:**
6 **Moisture Content and Particle-Size Effects**

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ABSTRACT

17 Spent coffee ground (SCG) is a food waste with promising potential for reuse in pilot-
18 to-industrial scale processes provided that storage and handling issues are overcome. Here
19 some key bulk and flow properties of SCGs were determined with FT4 rheometer, for
20 powders with different particle-size distribution ($249.1 \leq d_v \leq 583.1 \mu\text{m}$) and moisture content
21 ($2.8\% \leq MC \leq 62.5\%$). These properties were used to evaluate the design of mass-flow silo
22 hoppers following the classical Jenike theory. The SCGs flowability worsened by decreasing
23 d_v and increasing MC , with indexes between $1.09 \leq HR \leq 1.92$ and $2.5 \leq FF \leq 15.0$. The minimum
24 hopper inclination and outlet diameter ranged from 9.9° to 17.1° and 0.40 to 1.00 m. A
25 sensitivity analysis for the hopper design was performed, and a densification equation was
26 coupled to Jenike's method to ease future hopper designs for SCGs with different properties.
27 Ultimately, the results showed that careful consideration must be given to d_v and MC to
28 design effective devices to handle SCGs.

29 **Keywords:** biomass, silo, rheometer, powder handling, Jenike.

30 **1 Introduction**

31 Coffee, which is an agricultural product with distinguished taste and aroma, is widely
32 used as an ingredient in the food, pharmaceutical, and cosmetic industries, as well as
33 consumed as a beverage. It is a commodity traditionally produced in emerging countries, such
34 as Brazil, Colombia, and Vietnam, that generated combined revenue of around US\$ 11 billion
35 in 2019, which is a major contribution to the countries' trade market (Voora et al., 2019).
36 Over the last decade, global coffee consumption has increased by around 2% annually,
37 reaching almost 10 million tonnes in 2019 (International Coffee Organization, 2019). Owing
38 to the expected growth of the world's population by 25% until 2050, from 7.7 to 9.7 billion
39 people (United Nations, 2019), coffee is likely to play an even bigger role in the coming
40 decades.

41 Almost 50% of global coffee production is processed for instant coffee making
42 (Mussatto et al., 2011). In the soluble coffee industry, coffee fruit and beans are initially
43 processed into roasted coffee through some separation, drying, milling, and roasting steps,
44 and then soluble coffee powder is obtained from steaming extraction and spray-drying
45 (McNutt and He, 2019; Silva et al., 1998). Spent Coffee Ground (SCG) is the main solid
46 residue generated in this process, at a rate of 2.5 million tons per year. It has a low ash
47 content, and a high heating value similar to that of coal (25 kJ/kg) (Massaro Sousa and
48 Ferreira, 2019a). These characteristics allow using SCG powders to generate renewable
49 energy and steam within the industry, hence contributing to an attractive energy balance in
50 this process.

51 A general search in the Science Direct database shows that to date, about 1,000 research
52 papers have been published focusing on SCGs, with a significant increase of interest in this
53 topic recently, as the rate of publication has grown from 2 papers/year back in the 90s to
54 about 250 papers in 2020. Overall, these papers focused on reporting physico-chemical

55 properties for spent coffee grounds (Ballesteros et al., 2014; Massaro Sousa and Ferreira,
56 2019b; Mussatto et al., 2011; Silva et al., 1998) and on a wide variety of applications,
57 including drying and dewatering (Gómez-de la Cruz et al., 2015; Rocha et al., 2021; Tun et
58 al., 2020), feeding of reactors (Massaro Sousa et al., 2020a, 2020b; Massaro Sousa and
59 Ferreira, 2020a), solid-state fermentation (Murthy and Naidu, 2012), production of biofuels
60 (Al-Hamamre et al., 2012; Kondamudi et al., 2008), extraction of bioactive and antioxidant
61 compounds (Ballesteros et al., 2017; Brazinha et al., 2015; Karmee, 2018), preparing
62 biopolymeric films for food packaging (Coelho et al., 2021; Thiagamani et al., 2017),
63 combustion, gasification, and pyrolysis (Campos-Vega et al., 2015; Kelkar et al., 2015;
64 McNutt and He, 2019; Silva et al., 1998) and so on.

65 Some key bottlenecks for implementing the previous applications on the pilot and
66 industrial levels are related to the storage and handling of SCGs throughout the units. For
67 instance, it is paramount to design silos with a stable discharge of solids at predictable flow
68 rates, so that they can be used as reliable solid feeders or as intermediary/storage vessels to
69 suppress eventual process instabilities (Barletta et al., 2015; Dai et al., 2012; Ilic et al., 2018;
70 Ramírez-Gómez, 2016). While trial-and-error methods can be used for this design, the results
71 are often disappointing, with the presence of dead zones of solids within the hopper or no
72 solids flow out of the silo. Moreover, in the case of biomass residues such as SCGs, the
73 particle-size distribution, moisture content, and flow attributes vary due to the processing,
74 thus enhancing the difficulties associated with these solids' handling and hopper design.

75 Recently, some physical and flow properties of dry and moist SCG samples have been
76 determined for the basic understanding of SCGs flowability and compressibility (i.e. repose
77 angle, Hausner ratio, and bulk density) (Massaro Sousa and Ferreira, 2019a, 2019b).
78 However, there is still a gap in knowledge concerning the measurement of flow properties for
79 SCGs with shearing cells, and on using these properties for equipment design.

80 Therefore, this paper is aimed at understanding the flow pattern of industrial food waste
81 with promising potential for reuse, as well as assisting its storage and handling. First, some
82 key physical and flow properties of SCGs with different particle-size distribution and
83 moisture content were measured with a rheometer. Then, these properties were used to
84 investigate the design of silo hoppers for the effective mass-flow discharge of powders.

85 **2 Material and Methods**

86 **2.1 Materials**

87 The SCG samples were prepared by brewing a commercial blend of Arabica and
88 Robusta grains (Três Corações, São Carlos-SP, Brazil). The powders were oven-dried at
89 105 ± 2 °C for 24 h and sieved into three base samples named A_{100} , B_{100} , C_{100} . Sample A_{100} has
90 a particle-size distribution between 600 and 500 μm , while the size of sample B_{100} ranges
91 from 500 and 300 μm , and C_{100} lies between 300 and 150 μm .

92 Additional dry samples were prepared by mixing the coarser samples with the finest one
93 (C_{100}) in a percentage of 10% and 20% in mass, originating samples $A_{90}C_{10}$, $A_{80}C_{20}$, $B_{90}C_{10}$,
94 and $B_{80}C_{20}$. Finally, the base samples were humidified to 20% and 60% on a wet basis by
95 adding water in a glass flask, which was sealed and stored at 4 °C for 60 h. After every 24 h,
96 the flask was opened and the powder was homogenized to ensure uniform water distribution.
97 The moist samples are designated $A_{100}^{20\%}$, $A_{100}^{60\%}$, $B_{100}^{20\%}$, $B_{100}^{60\%}$, $C_{100}^{20\%}$, and $C_{100}^{60\%}$.

98 As previously mentioned, a total of seven dry and six moist SCG powders were
99 prepared, aiming at understanding the effect of samples' size and moisture content on SCG
100 flow properties, densification kinetics, and silo hopper design. These samples were selected to
101 cover a wide range of powder properties that are commonly observed in the industrial
102 processing of this biomass waste (Silva et al., 1998).

103 2.2 Characterization of SCGs properties

104 Particle-size distribution and mean diameter (De Brouckere diameter - d_v) of the dry
105 samples was measured, in duplicate, by laser diffraction technique using BlueWave model
106 equipment (MicroTrac, Pennsylvania, USA) with air as dispersion media. Particle sizes from
107 0.01 to 2,800 microns can be accurately measured with this equipment, which covers the size
108 range for the SCGs.

109 Moisture content (MC) of SCG samples was measured with an infrared drying balance
110 model IV-2000 (Gehaka, São Paulo, Brazil) in duplicate. The moisture contents are reported
111 in wet basis.

112 Bulk density of the samples was evaluated under different normal pressures (N) applied
113 to the powder bed in an FT4 rheometer (Freeman Technology, Tewkesbury, UK). First, a
114 known quantity of SCGs is conditioned on the rheometer and based on the volume occupied
115 by the powders, the loose bulk density (ρ_{bl}) is determined. Then, normal pressures of 0.5, 1, 2,
116 4, 6, 8, 10, 12, and 15 kPa are sequentially applied with a vented piston that allows air to
117 escape from the bed out of the vessel during compression. The reduction of powders volume
118 is measured, and the bulk density at each N is obtained. The Hausner ratio (HR) is calculated
119 from the ratio of the consolidated bulk density measured at 15 kPa (ρ_{bc}) and ρ_{bl} , as proposed
120 by (Baião et al., 2018).

121 2.3 Granular shear and wall friction measurements

122 Powder shear and wall friction measurements were performed in an FT4 rheometer with
123 shear cell accessory: 50 mm of internal diameter and 85 cm³ in volume vessel, a 48 mm shear
124 head diameter and 48 mm diameter disc of stainless steel. The SCG sample was initially
125 homogenized and pre-consolidated within the rheometer by the standard procedure of the
126 equipment, allowing air to escape from the bed out of the vessel in the pre-consolidation
127 stage. After, pre-shear was performed at normal consolidation stresses of 15, 9, 6, and 3 kPa,

128 followed by a shear step to estimate incipient failure (of the consolidated sample) at 5
129 different normal stress conditions induced in the powder bed for each level of consolidation,
130 according to ASTM D7891-15 (American Society for Testing Material, 2015). The assays
131 were performed in duplicate for all SCG samples.

132 From this experiment, the yield locus and effective yield locus are obtained. By plotting
133 the Mohr circles, some flow parameters for the powders are determined, such as cohesion (c),
134 angle of internal friction (σ), effective angle of internal friction (δ), unconfined yield strength
135 (UYS), major consolidating stress (MCS), and flow function (FF). The FF is obtained from
136 the ratio of UYS to MCS and is used as a parameter to describe the strength of a bulk solid.
137 Depending on FF , the powder flowability is classified as *free-flowing* ($FF \geq 10$), *easy-flowing*
138 ($4 \leq FF < 10$), *cohesive* ($2 \leq FF < 4$), *very cohesive* ($1 \leq FF < 2$), or *not flowing* ($FF < 1$).

139 Finally, the wall friction angle (ϕ_w) of the powders was estimated by measuring
140 frictional resistance between a metallic disc and SCG samples under consolidation stress
141 from 3 to 15 kPa, in duplicate. The disc is made of stainless steel, which is a material
142 commonly used in the food industry hoppers.

143 2.4 Conical hopper design

144 Design of the conical hopper for mass-flow discharge consists of using the measured
145 flow properties with the rheometer for determining the minimum hopper half-angle (θ_m), and
146 minimum hopper outlet size (D_m). In this way, θ_m is calculated according to (Oginni and
147 Fasina, 2018):

$$\theta_m = 90^\circ - 0.5 \cos^{-1}[(1 - \sin \delta)/2 \sin \delta] - \beta \quad (1)$$

$$\beta = [\phi_w + \sin^{-1}(\sin \phi_w / \sin \delta)]/2 \quad (2)$$

148 After calculating θ_m from Eqs. (1) and (2), it is recommended to adopt a margin of
149 safety for θ_m to allow for differences in the wall surfaces or slight variations in the bulk solid

150 properties, then the angle should be reduced by 3° . The minimum hopper outlet size is
 151 calculated by (Oginni and Fasina, 2018):

$$D_m = H(\theta_m)\sigma_{cr}/(\rho_b g) \quad (3)$$

$$H(\theta_m) = (130 + \theta_m)/65 \quad (4)$$

152 The critical applied stress (σ_{cr}) represents the limiting value of the unconfined yield
 153 strength at which a stable arch can be formed. This value can be obtained from the
 154 intersection of the powder flow function (FF) with the hopper flow factor line (ff) in a graph
 155 of the major consolidation stress (x-axis) versus the unconfined yield stress (y-axis). Note that
 156 ff is a straight-line through the origin with a slope equal to the inverse of ff (Fitzpatrick et al.,
 157 2004).

158 Although ff can be obtained from the design charts shown in Jenike's famous Bulletin
 159 163 (Jenike, 1964), algebraic expressions derived from these charts are preferred as they can
 160 be readily implemented in spreadsheets (Arnold and McLean, 1976; Condotta, 2017; Enstad,
 161 1975). The set of equations are shown below:

$$ff = Y(1 + \sin \delta)H(\theta_m)/[2(X - 1) \sin \theta_m] \quad (5)$$

$$X = 2 \sin \delta / (1 - \sin \delta) [1 + \sin(2\beta + \theta_m) / \sin \theta_m] \quad (6)$$

$$Y = (A + B) / C \quad (7)$$

$$A = 2[1 - \cos(\beta + \theta_m)] \sin \theta_m \quad (8)$$

$$B = \sin \beta \sin(\beta + \theta_m) \sin(\beta + \theta_m) \quad (9)$$

$$C = (1 - \sin \delta) \sin(\beta + \theta_m) \sin(\beta + \theta_m) \sin(\beta + \theta_m) \quad (10)$$

162 There are three possible scenarios concerning the intersection of FF and ff (in the
 163 positive x-y quadrant) that might affect determining σ_{cr} , and consequently D_m :

- 164 i) if there is an intersection between FF and ff , σ_{cr} is determined at the y-axis and used
 165 to calculate D_m with Eq (3);

166 ii) if there is no intersection, and FF lies above ff , the powder does not flow under
167 gravitational discharge or with the proposed hopper wall material;
168 iii) if there is no intersection, and FF lies below ff , from the perspective of cohesive
169 arch formation, the powder will flow with any D_m as the applied stress at the hopper
170 outlet overcomes the unconfined yield strength of the arch. In this case, the
171 minimum hopper outlet can be selected either to avoid interlocking effects (usually
172 D_m is 10 to 12 times the diameter of the largest particle (Oginni and Fasina, 2018))
173 or by other non-standardized criteria based on the handling experience of specific
174 powders or fitted correlations (Chen et al., 2012; Fitzpatrick et al., 2004; Salehi et
175 al., 2019).

176 3 Results and Discussion

177 3.1 Physical properties of SCGs

178 Some key properties of the SCG samples are presented in Table 1, such as the volume
179 mean diameter, moisture content, as well as the loose and consolidated bulk densities
180 measured under pressures of 0 and 15 kPa, respectively. Hausner ratio ($HR=\rho_{bc}/\rho_{bl}$) is an
181 important parameter often used for industrial quality control of pelletizing and feeding
182 operations as it quantifies the flowability and compressibility of powders. Based on this
183 parameter, the lower is the HR , the better is the flowability/compressibility of the sample,
184 which generally means a lower likelihood of operational problems related to powders'
185 handling.

186 It can be observed from Table 1 that the flowability of SCGs worsens as the moisture
187 content increases and as the sample's mean diameter decreases. For example, the flowability
188 of the dry and coarsest sample A_{100} is categorized as *excellent*, whereas the flowability of the
189 finest sample C_{100} is categorized as *passable*. The HR of the dry powder mixtures are

190 intermediary to those of the base samples. Besides, the *HR* increases with the moisture
 191 content, then the flowability of sample $A_{100}^{60\%}$ is classified as *very poor*, while $A_{100}^{20\%}$ is
 192 *good*, for example. The effect of the moisture content and particle-size distribution on SCGs
 193 flowability agree with previous literature results (Massaro Sousa and Ferreira, 2019a).

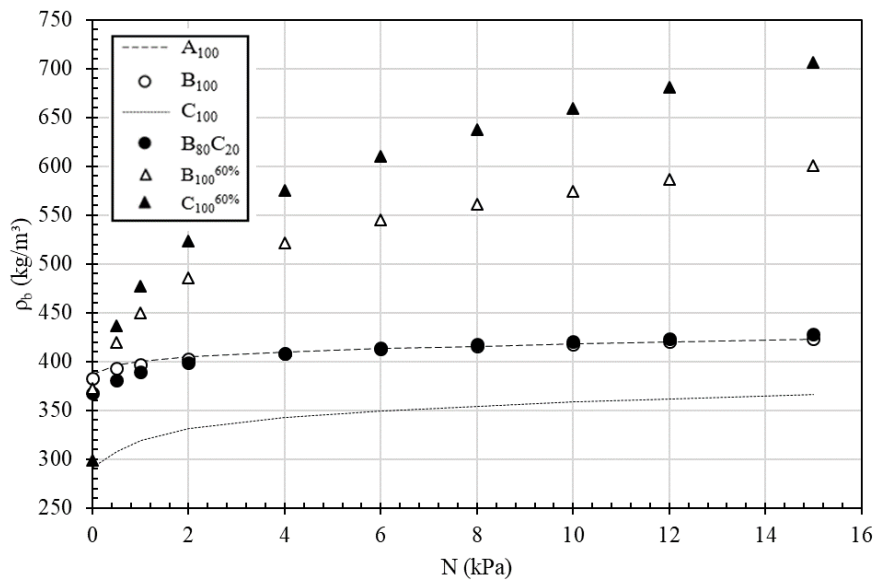
194 **Table 1.** Physical properties of spent coffee ground powders

SCG Sample	d_V (μm)	MC (% w.b.)	ρ_{bl} (kg/m^3)	ρ_{bc} (kg/m^3)	HR (-)	Flowability classification
A_{100}	583.1	5.4	386	423	1.09	Excellent
$A_{100}^{20\%}$	-	25.1	368	436	1.18	Good
$A_{100}^{60\%}$	-	58.7	409	609	1.49	Very Poor
B_{100}	442.2	2.8	383	424	1.10	Excellent
$B_{100}^{20\%}$	-	21.4	367	443	1.20	Fair
$B_{100}^{60\%}$	-	62.5	373	610	1.64	Very, Very Poor
C_{100}	249.1	3.1	292	367	1.26	Passable
$C_{100}^{20\%}$	-	21.7	309	412	1.35	Poor
$C_{100}^{60\%}$	-	61.0	299	574	1.92	Very, Very Poor
$A_{90}C_{10}$	549.7	-	405	464	1.14	Good
$A_{80}C_{20}$	516.3	-	381	452	1.19	Fair
$B_{90}C_{10}$	422.9	-	372	424	1.14	Good
$B_{80}C_{20}$	403.6	-	368	428	1.16	Good

195 3.2 Densification kinetics of SCGs

196 Evolution of the powder bulk density with the applied pressure is known as the
 197 densification curve, with initial and final points as the loose and consolidated bulk densities.
 198 The values for ρ_{bl} and ρ_{bc} are presented in Table 1 for all SCG samples. The points and the
 199 curvature of the densification curve depend on the bulk material and its properties, such as the
 200 particle-size distribution, and moisture content. In this way, assessing the densification of
 201 SCGs with different properties is crucial for the effective design and operation of units that
 202 handle such biomass powders.

203 The effect of the particle-size distribution and moisture content on the densification
 204 curves of SCGs is shown in Fig. 1. The dry samples exhibit similar densification patterns,
 205 with a steep increase in the bulk density prior to $N=4$ kPa, which represents around 70% of
 206 the consolidated bulk density, and a nearly constant bulk density from $N=10$ kPa onwards,
 207 indicating that the maximum bed compaction has been achieved. More specifically, samples
 208 A_{100} and B_{100} have similar bulk densities, whereas the curve of the powder mixture $B_{80}C_{20}$ is
 209 slightly shifted downwards. Finally, the finest powder C_{100} has the lowest bulk density which
 210 might be attributed to enhanced cohesion effects of van der Waals origin (Castellanos, 2005).



211 **Fig. 1.** Bulk density (ρ_b) as a function of the applied normal stress for selected spent coffee
 212 ground samples
 213

214 Adding water to the dry samples increases the bulk density since air voids become
 215 partially filled with water, which has a density thousand times greater than the air. For the wet
 216 samples, there is a consistent increase in ρ_b with increasing N , and possibly the maximum bed
 217 compaction has not been achieved at $N=15$ kPa. In summary, the densification process is
 218 slower for samples with higher cohesion, such as those containing finer particles or higher
 219 moisture content. Although only a few SCG samples are shown in Fig. 1, the behavior
 220 previously described covers all tested powders.

221 In a previous study (Massaro Sousa and Ferreira, 2019b), the densification of dry SCGs
222 was assessed by tapping, which means that the powder bed is compacted with the bed weight
223 and not by applying external forces. In general, powder beds 8% denser were achieved with
224 tapping when compared to the applied pressure compaction, which can be attributed to: i) the
225 facilitated rearrangement of particles in the voids promoted by the successive bed vibrations,
226 and ii) limited range of the applied pressure to affect the compaction in the lower portions of
227 the bed. From the practical perspective, these results highlight that for an accurate equipment
228 design some assumptions on the powder densification mechanism should be performed
229 beforehand, i.e., by considering the extent of variation of the bulk density within the
230 equipment as a consequence of the applied normal pressures, and particles rearrangement due
231 to vibration.

232 In the next section, an analysis is carried out to model the densification curves of SCGs.
233 The aim is to use a single equation to describe the densification process with fitting
234 parameters correlated to SCGs properties. In this way, the bulk density of a certain SCG
235 sample can be readily estimated for a given N .

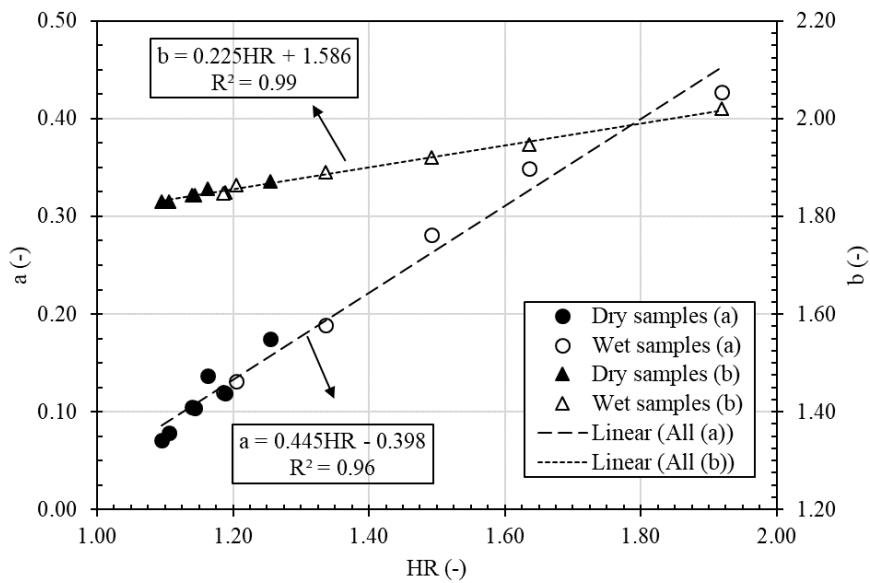
236 3.3 Modelling of SCGs densification

237 In a previous study, the two-parameter equation of Kawakita and Ludde (Eq. 11)
238 (Kawakita and Lüdde, 1971) accurately predicted the densification curves of dry SCGs
239 submitted to tapping. The parameters a and b of the equation could be correlated with the
240 physical properties of the samples, such as the mean diameter and HR (Massaro Sousa and
241 Ferreira, 2019b). Here, Eq. (11) is tested for predicting the densification behavior of dry and
242 wet SCGs submitted to normal pressures. Since the relative density (D) is the ratio of bulk to
243 solid density ($\rho_s=1,315 \text{ kg/m}^3$ for SCGs (Massaro Sousa and Ferreira, 2019a), the bulk density
244 as a function of N can be explicitly calculated by Eq. (12).

$$(D - D_{bl})/D = abN/(bN + 1) \quad (11)$$

$$\rho_b = \rho_{bl}/[1 - abN/(bN + 1)] \quad (12)$$

245 The parameters a and b are shown in Fig. 2 as a function of the HR of the samples.
 246 From Fig. 2, both parameters in Eq. (11) increase as HR rises. These findings are in line with
 247 expectations since high HR indicates that powder bulk density changes significantly
 248 throughout compaction, then high values for a and b are necessary to describe the steeper
 249 variation on the kinetic curves of these powders.



250 **Fig. 2.** Parameters a and b as a function of the samples' Hausner ratio (HR)
 251

252 Linear equations fitted the relationship between the parameters and HR accordingly
 253 with regression coefficients of 0.99 and 0.96 for Eqs. (13) and (14), respectively. Also, the
 254 data are randomly distributed around the lines of the fittings, which is evidence of non-biased
 255 fittings.

$$a = 0.445HR - 0.398 \quad (13)$$

$$b = 0.225HR + 1.586 \quad (14)$$

256 By using Eqs. (12) to (14), it is possible to estimate the bulk density of SCGs for a
 257 given N provided that both the HR and loose bulk density for the sample are known (see

258 Table 1). Difference between experimental and predicted values of bulk density is on an
259 average of 24% in the range of $0 \leq N \leq 15$ kPa. Nevertheless, we recommend using Eqs. (12)
260 and (13) for predicting ρ_b over $N \geq 2$ kPa as the mean differences lie below 13%. For $N < 2$ kPa
261 the differences reach 40% because the data become more dispersed as the loose bulk
262 condition is approached.

263 From the above, information on SCGs bulk density can be readily obtained for various
264 normal consolidation pressures, which is useful for equipment design and process control.

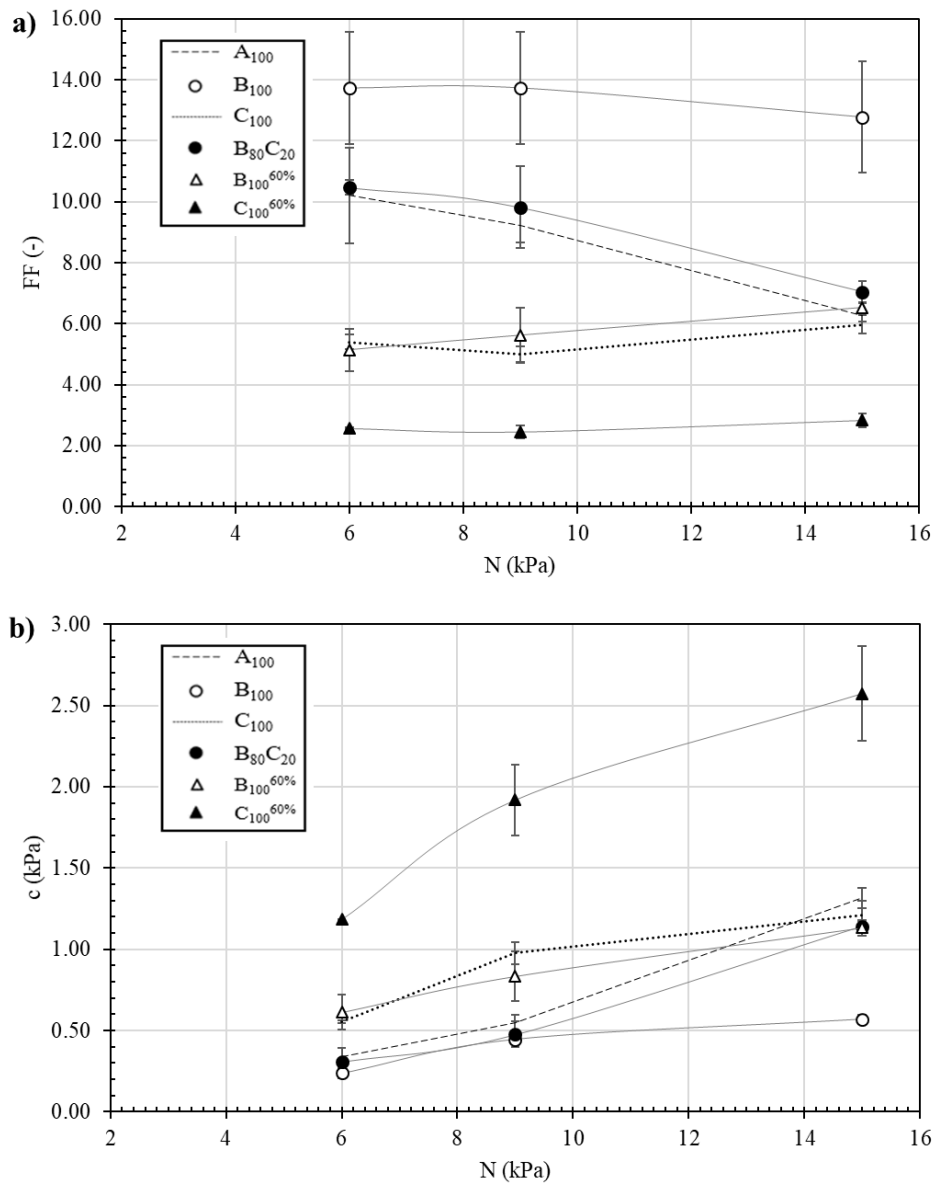
265 3.4 Flow properties of SCGs

266 In this section, the effect of the particle-size distribution and moisture content on the
267 SCG flow properties measured with the FT4 rheometer is analysed. The flow function and
268 cohesion of the powders are presented in Figures 3a and 3b, respectively, as a function of N .
269 Overall, increasing the consolidation pressure leads to lower powder flow functions (Fig. 3a)
270 and higher powder cohesion (Fig. 3b), as particle-particle contacts are enhanced within the
271 rheometer under higher N .

272 Powders with higher FF have better flowability; hence, the sample with the finest
273 particles (C_{100}) has the worst flowability among the dry samples. This is due to the higher
274 cohesion of this sample motivated by its greater specific surface area that enhances cohesive
275 forces of van der Waals nature (Castellanos, 2005). Concerning the other dry powders, the
276 flowability of sample A_{100} is worse than sample B_{100} probably due to particle-particle
277 interlocking effects within the rheometer for the coarsest sample, whereas, intermediary FF
278 values are observed for the mixtures of coarse and fine particles.

279 By adding water to the dry SCG samples, cohesive forces of liquid bridge nature
280 become important and powder flowability deteriorates as the moisture content increases. In
281 Fig. 3a and 3b, for example, the wet sample $B_{100}^{60\%}$ exhibits similar FF and cohesion than
282 that of sample C_{100} , whereas sample $C_{100}^{60\%}$ has the worst flowability among all SCG samples

283 due to a combined effect of liquid bridges and van der Waal interactions, since smaller
 284 particles saturate its surface at reduced moisture content.



285

286

287 **Fig. 3.** Flow properties as a function of the consolidation stress for selected spent coffee
 288 ground samples: a) flow function and b) cohesion

289

The previous conclusions concerning the *FF* and cohesion trends are also valid for the
 290 SCG samples not shown in Fig. 3. The mean value of *FF* for all samples is presented in Table
 291 2 along with the standard deviation and flowability classification. Although most of the
 292 samples are categorized as *easy-flowing* powders with $10 < FF < 4$, it is noticeable that *FF*

293 decreases with increasing moisture content and with decreasing particle mean diameter,
 294 leading to a *cohesive* behavior for sample C₁₀₀^{60%}.

295 **Table 2.** Averaged values for SCG properties measured with the rheometer and flowability
 296 classification

SCG Sample	δ (°)	ϕ_w (°)	FF (-)	Flowability classification
A ₁₀₀	40.3 ± 0.4 ^a	25.0 ± 2.0 ^a	9.0 ± 2.0 ^a	Easy flowing
A ₁₀₀ ^{20%}	41.8 ± 0.5 ^b	27.5 ± 0.3 ^a	6.3 ± 0.9 ^b	Easy flowing
A ₁₀₀ ^{60%}	42.5 ± 0.9 ^b	26.0 ± 1.0 ^a	6.0 ± 1.0 ^b	Easy flowing
B ₁₀₀	39.8 ± 0.4 ^a	25.0 ± 3.0 ^a	15.0 ± 4.0 ^c	Free flowing
B ₁₀₀ ^{20%}	41.0 ± 0.8 ^{ab}	27.2 ± 0.5 ^a	8.0 ± 2.0 ^{ab}	Easy flowing
B ₁₀₀ ^{60%}	43.1 ± 0.9 ^b	27.5 ± 0.6 ^a	5.0 ± 1.0 ^b	Easy flowing
C ₁₀₀	40.0 ± 0.7 ^a	27.0 ± 2.0 ^a	5.3 ± 0.5 ^b	Easy flowing
C ₁₀₀ ^{20%}	40.9 ± 0.5 ^{ab}	28.8 ± 0.7 ^{ab}	5.1 ± 0.3 ^b	Easy flowing
C ₁₀₀ ^{60%}	48.8 ± 0.9 ^c	30.8 ± 0.9 ^b	2.5 ± 0.2 ^d	Cohesive
A ₉₀ C ₁₀	40.9 ± 0.7 ^{ab}	24.0 ± 3.0 ^a	8.0 ± 2.0 ^{ab}	Easy flowing
A ₈₀ C ₂₀	41.1 ± 0.6 ^{ab}	25.0 ± 2.0 ^a	6.9 ± 0.8 ^{ab}	Easy flowing
B ₉₀ C ₁₀	40.2 ± 0.4 ^a	26.0 ± 2.0 ^a	8.0 ± 2.0 ^{ab}	Easy flowing
B ₈₀ C ₂₀	39.8 ± 0.5 ^a	25.0 ± 2.0 ^a	9.0 ± 2.0 ^a	Easy flowing

297 * Values with different letters in the same column are significantly different at the 0.05 significance level

298 The average values for the effective angle of internal friction (δ) and wall friction angle
 299 (ϕ_w) are presented in Table 2 along with their standard deviation, measured between $N=3$ and
 300 15 kPa. Similar to the cohesion and FF , both angles vary when N changes from 3 to 15 kPa:
 301 while δ exhibits a slight increase as N rises, ϕ_w decreases with increasing N . Besides, δ and ϕ_w
 302 increases as the SCGs flowability worsens, i.e., with decreasing particle size and increasing
 303 moisture content. These trends agree with results from the literature (Marinelli and Carson,
 304 1992).

305 In practice, a minor worsening of powder flow attributes may compromise the operation
 306 of various types of industrial equipment, such as those for the feeding and storing of solids.

307 Some evidence of the effect of powder flowability on the solid feeder's performance has been
308 previously assessed in handling dry and moist SCGs to reactors with L-valve and spouted bed
309 feeding devices (Massaro Sousa and Ferreira, 2020a, 2020b). The results of HR and FF
310 showed in Table 1 and Table 2 indicate that both indices are sensitive to the SCG size and
311 moisture content; hence they might be useful for process monitoring and control.

312 In the next section, the design of silo hoppers is addressed aiming at an effective mass-
313 flow discharge of SCGs with different properties. Apart from the bulk density (Sections 3.2
314 and 3.3), the effective angle of internal friction (δ) and wall friction angle (ϕ_w) shown in Table
315 2 are the properties used for the design of hoppers according to the classical Jenike theory.

316 3.5 Hopper design for SCGs

317 In the design of conical hoppers for mass-flow discharge, the minimum hopper angle
318 (θ_m) and the minimum outlet diameter (D_m) are determined based on the powder flow
319 properties. By using the set of Eqs. (1) to (10) and the values of δ and ϕ_w (Table 2), it is
320 possible to obtain θ_m and the hopper flow factor (ff) for each SCG sample as shown in Table
321 3.

322 The results of θ_m are in line with expectations, and the general trend is that the worse the
323 samples' flow properties are, the greater is the hopper inclination to achieve a mass-flow
324 discharge of SCGs. For example, more inclined hoppers (lower θ_m) are required to make
325 sample C₁₀₀ flow compared to those required for coarser samples A₁₀₀ and B₁₀₀; Moreover,
326 increasing the moisture content of sample C₁₀₀ from a dry powder to around 60% drops θ_m in
327 almost 30%, from 14.1 to 9.9°. The ff is a function of the hopper design and its trend followed
328 the θ_m behavior, as shown in Table 3, with lower values of ff as the sample flow attributes
329 worsen.

330 A common rule of thumb used to achieve mass-flow discharge with powders of
331 unknown flow properties consists of using $\theta_m = 20^\circ$, however, it would not be appropriate to

332 handle the SCG samples analysed, which highlights the impact of the findings of this study.
 333 In real operations, it is likely that funnel discharge or no-flow of SCGs occur with $\theta_m = 20^\circ$;
 334 hence, compromising process stability, performance, automation, and safety.

335 **Table 3.** Results of the silo design for dry and wet spent coffee ground samples

SCG Sample	θ_m (°)	ff (-)	σ_{cr} (Pa)	D_m (m)	D^* (m)
A ₁₀₀	17.0	1.43	-1266	-	0.02
A ₁₀₀ ^{20%}	13.6	1.38	-871	-	0.02
A ₁₀₀ ^{60%}	15.7	1.37	992	0.57	-
B ₁₀₀	17.0	1.45	-920	-	0.02
B ₁₀₀ ^{20%}	13.9	1.40	-1490	-	0.02
B ₁₀₀ ^{60%}	13.7	1.35	1351	0.83	-
C ₁₀₀	14.1	1.42	509	0.40	-
C ₁₀₀ ^{20%}	11.6	1.39	-271	-	0.59
C ₁₀₀ ^{60%}	9.9	1.23	1333	1.00	-
A ₉₀ C ₁₀	18.4	1.43	-718	-	0.06
A ₈₀ C ₂₀	17.1	1.41	-715	-	0.10
B ₉₀ C ₁₀	15.6	1.43	-1024	-	0.06
B ₈₀ C ₂₀	17.0	1.45	-683	-	0.10

336 Additionally to the cone angle limitation, for sample C₁₀₀ and the ones with 60% of
 337 moisture content, a minimum hopper diameter (D_m) is required to prevent the formation of
 338 cohesive arches (see case iii, Section 2.4). As shown in Table 3, D_m increases as the particle
 339 size decreases, thus sample C₁₀₀^{60%} has the highest D_m followed by B₁₀₀^{60%} and A₁₀₀^{60%}.

340 For the other SCG samples, the intersection between ff and FF is classified as case ii
 341 (Section 2.4), which means that the powders might flow for any outlet diameter according to
 342 Jenike's theory because the hopper wall inclination is enough to break up cohesive arches.
 343 Therefore, in these cases, the outlet diameter is usually set to avoid interlocking effects, with
 344 D^* equal to 12 times the size of the largest particle. Nevertheless, since even the bigger SCG

345 sample diameter is smaller than 1 mm, the range for D^* would be 0.66-0.44 cm, which is far
346 from reasonable for industrial operations.

347 In the literature, there are some examples of D_m that were proposed based on the
348 author's handling experience for specific powders rather than with the previous rule of thumb.
349 In this way, a more conservative design for the outlet diameter of some SCG samples,
350 denoted by the symbol D^* in Table 3, might be based on the following premises:

- 351 - D^* of sample $C_{100}^{20\%}$ was obtained by linearly interpolating D_m of samples C_{100} and
352 $C_{100}^{60\%}$ concerning the moisture content reported in Table 1;
- 353 - Sample B_{100} and one with 30% of moisture content presented stable discharge from
354 silo hoppers of $\theta_m=30^\circ$ and $D_m=2.1$ cm in a previous study (Massaro Sousa and
355 Ferreira, 2020a). Therefore, $D^*=2.1$ cm was set for samples B_{100} , and $B_{100}^{20\%}$,
356 however, without assertiveness on whether it is a mass- or funnel-flow discharge. As
357 samples A_{100} and $A_{100}^{20\%}$ have similar flow properties than B_{100} , and $B_{100}^{20\%}$, the
358 same D^* was set to these powders.
- 359 - D^* of samples $A_{90}C_{10}$, $A_{80}C_{20}$, $B_{90}C_{10}$, and $B_{80}C_{20}$ were obtained based on a
360 weighted average of D_m of samples A_{100} and C_{100} with respect to the fraction of
361 fines in the mixture.

362 It should be noted that the reported values for D_m vary $\pm 0.5\%$ and 1.3% by considering
363 the upper and lower limits of the averaged δ and ϕ_w shown in Table 2, respectively.
364 Meanwhile, θ_m vary 0.5% and 9.0% in the same range of variation for δ and ϕ_w . In the next
365 section, the effect of variations on the main parameters used for determining θ_m and D_m are
366 discussed in detail.

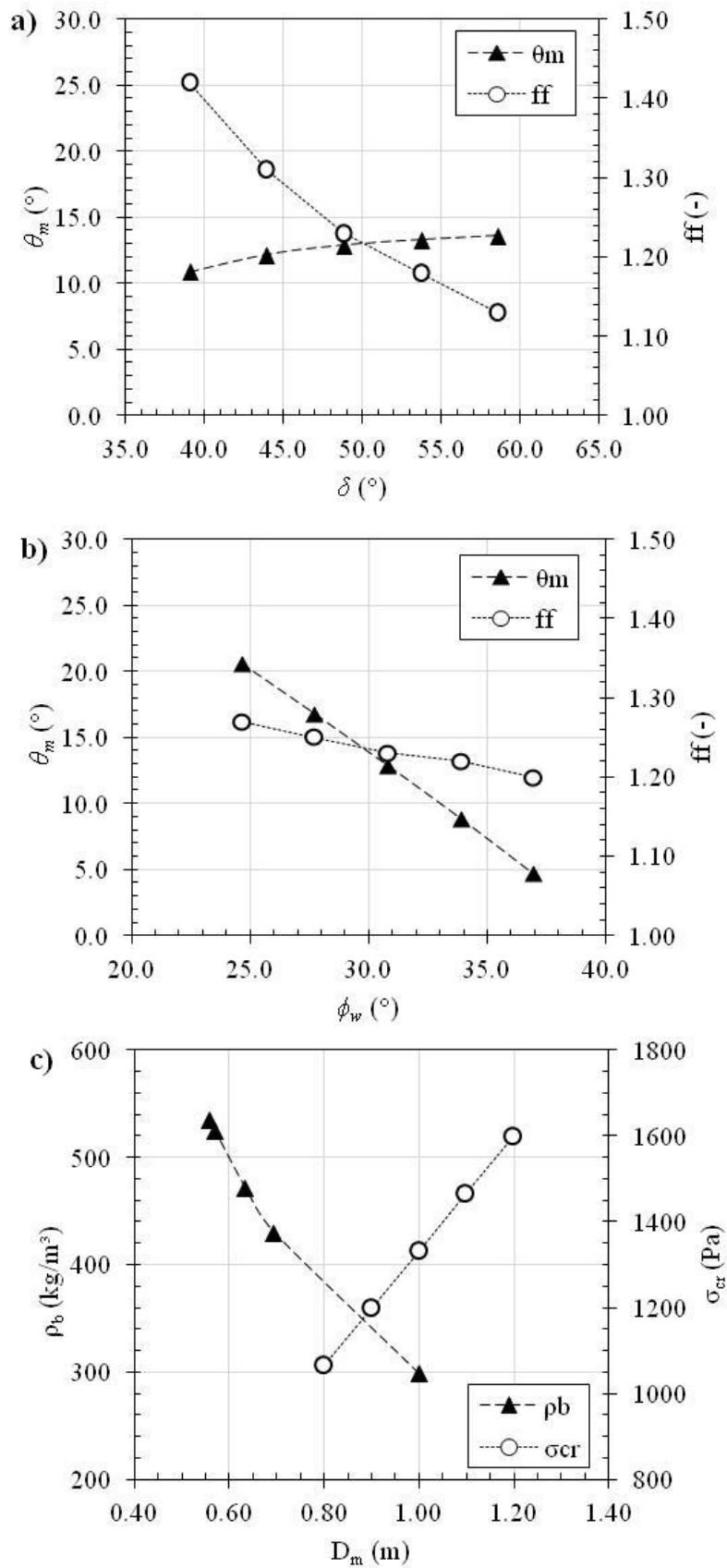
367 3.6 Sensitivity of hopper design for SCGs

368 The particle-size distribution and moisture level of spent coffee grounds are not
369 controlled in industrial processes due to its residue-based nature. Thus, there is some

370 variability on samples' flow and bulk properties, as illustrated in the previous sections, which
371 ultimately might affect the design of hoppers for the mass-flow discharge of these biomass
372 powders.

373 The effect of δ and ϕ_w on the minimum hopper half-angle and hopper flow factor is
374 depicted in Fig. 4a and 4b, respectively. Overall, θ_m is mainly affected by variations in ϕ_w , and
375 steeper hoppers are required to achieve mass flow discharge of powders with higher ϕ_w . On
376 the other hand, ff is mostly affected by δ following an inversely proportional linear
377 relationship. For intersections between ff and FF classified as the case i (Section 2.4), it
378 means that samples with lower values of δ have greater ff and σ_{cr} , which leads to wider outlet
379 diameters required to achieve mass-flow discharge of solids from the hopper.

380 Finally, in Fig. 4c it is shown that both the bulk density and σ_{cr} (or implicitly FF) play a
381 major role in the calculated outlet hopper diameter. For example, for intersections between ff
382 and FF classified as case i (Section 2.4), the lower is the FF (i.e. powders with worse
383 flowability) the higher is σ_{cr} ; hence, wider hopper diameters are required to achieve the mass-
384 flow discharge of SCGs. Furthermore, higher is the bulk density at the cone outlet, the smaller
385 is the required hopper diameter size for the gravity-driven, mass-flow discharge of solids. As
386 shown in Section 3.3, Eqs. (12) to (14) provide a reliable estimation of the bulk density for
387 dry and wet SCGs under different normal pressures; hence, these equations coupled to
388 Jenike's method are useful to meet specific requirements for silos with SCGs in the pilot and
389 industrial-scale plants, as well for improving automation and process monitoring.



390
 391 **Fig. 4.** Hopper flow factor (ff) and hopper half-angle (θ_m) with respect to variations in a) δ and
 392 b) ϕ_w , as well as hopper diameter response to changes in c) ρ_b and σ_{cr}

393 4 Conclusions

394 This study corroborates that the mean particle diameter and moisture content play an
395 important role in both bulk properties and flow attributes of SCGs, hence impacting the
396 design of silo hoppers for the effective mass-flow discharge of powders. Flowability of SCGs
397 deteriorated with decreasing particle-size and increasing moisture content.

398 From the practical point of view, silo hoppers with inclination and outlet diameter
399 between 9.9° to 17.1° , and 0.40 to 1.00 m are sufficient to handle most SCG powders. It is
400 also shown that a densification equation can be coupled to Jenike's method, which might
401 facilitate the further design of silo hoppers for SCGs with different properties.

402 The findings are valuable for solid-waste researchers and practitioners aiming at the
403 effective handling of SCGs. Future research could address the design of hoppers for other
404 relevant food wastes with different material properties, as well as numerical simulations to
405 investigate particle segregation effects on the hopper discharge for waste biomass powders.

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411 Nomenclature

<i>A</i>	Parameter calculated as per Eq. (8) (-)
<i>a</i>	Empirical parameter in Eq. (11) (-)
<i>B</i>	Parameter calculated as per Eq. (9) (-)
<i>b</i>	Empirical parameter in Eq. (11) (-)
<i>C</i>	Parameter calculated as per Eq. (10) (-)
<i>c</i>	Cohesion (kPa)
<i>D</i>	Relative density (-)
<i>D_{bl}</i>	Relative density at loose bulk condition (-)
<i>D_m</i>	Jenike's minimum hopper outlet size (m)
<i>D*</i>	Empirical minimum hopper outlet size (m)

d_v	De Brouckere mean diameter (μm)
ff	Hopper flow factor line (-)
FF	Flow function (-)
g	Gravity acceleration ($\text{m}\cdot\text{s}^{-2}$)
$H(\theta_m)$	Parameter calculated as per Eq. (4) (-)
HR	Hausner ratio (-)
MC	Moisture content (% w.b.)
MCS	Major consolidating stress (kPa)
N	Consolidating pressure (kPa)
UYS	Unconfined yield strength (kPa)
X	Parameter calculated as per Eq. (6) (-)
Y	Parameter calculated as per Eq. (7) (-)

Greek symbols

β	Parameter calculated as per Eq. (2) ($^\circ$)
ρ_b	Bulk density ($\text{kg}\cdot\text{m}^{-3}$)
ρ_{bl}	Loose bulk density ($\text{kg}\cdot\text{m}^{-3}$)
ρ_{bc}	Consolidated bulk density ($\text{kg}\cdot\text{m}^{-3}$)
ρ_s	Solid density ($\text{kg}\cdot\text{m}^{-3}$)
ϕ_w	Wall friction angle ($^\circ$)
θ_m	Jenike's minimum hopper half angle ($^\circ$)
σ	Angle of internal friction ($^\circ$)
σ_{cr}	Critical applied stress (Pa)
δ	Effective angle of internal friction ($^\circ$)

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