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# Caking behaviour of food powder binary mixes containing sticky and non-sticky powders

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## Research Highlights

- At least 20% “sticky” powder fraction was required to initiate caking.
- Different “non-sticky” powders can display very different caking behaviours in mixes depending on the particular “sticky” powder.
- All “non-sticky” powders greatly reduced the strong caking effect of the “stickiest” maltodextrin powder.
- Caking behaviour is highly influenced by the “sticky” powders ability to deform and flow.

# 1 **Caking behaviour of food powder binary mixes containing** 2 **sticky and non-sticky powders**

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## 9 **ABSTRACT**

10 Caking of food powders is highly undesirable. Many food powders are powder ingredient mixes  
11 and there is little work reported on the caking of food powder mixes. This study focusses on the  
12 caking of food powder binary mixes consisting of a “sticky” powder (whey permeate WP or  
13 maltodextrin MD) and a “non-sticky” powder (salt, flour or paprika). The powders were exposed  
14 to 76% relative humidity to make the WP and MD sticky. Force-displacement testing coupled  
15 with visual assessment of 2 particles in contact using a microscope were used to investigate the  
16 caking behaviour of the binary mixes. A “sticky” powder mass fraction of at least 20% was  
17 required to initiate caking and formation of weak cakes. Increasing percentage “sticky” powder  
18 fraction above the initial caking percentage resulted in progressively stronger cakes, however the  
19 rate of this progression was much less for the stickiest MD powder. The “non-sticky” powders  
20 and how they interacted with the “sticky” powders influenced the caking behaviour of the mix.  
21 For example, salt formed the strongest cakes in the WP mixes but formed the weakest in the MD  
22 mixes. Ability of a “sticky” powder to deform and flow influenced caking behaviour.

23 *Keywords:* Powders mixes; Powder caking; Glass transition.

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## 27 **1. Introduction**

28 Powder flow properties are important in handling and processing operations (Knowlton  
29 et al., 1994), as flow problems in hoppers and silos are commonplace problems for  
30 engineers and process operatives. Furthermore, bulk materials such as food powders can  
31 be very problematic whereby product may be rendered unusable due to severe caking.  
32 During handling, storage, processing and distribution to the final consumer, the powders  
33 may experience compaction and variations in temperatures and atmospheric humidities,  
34 which may alter the handling behaviour and appearance of the powders (Teunou and  
35 Fitzpatrick, 2000; Fitzpatrick et al., 2007). Water uptake by the powder is often a key  
36 cause of caking, thus it is very important to know the water sensitivity and the  
37 hygroscopicity of the powder components for predicting the kinetics of reduced  
38 flowability and caking (Fitzpatrick et al., 2010).

39 Many food powders contain amorphous glassy components, such as amorphous sugars  
40 and maltodextrins. The glass transition temperature ( $T_g$ ) is very important because  
41 amorphous components may become sticky (Aguilera et al., 1995; Kudra, 2003; Adhikari  
42 et al., 2005; Descamps et al., 2013) if the powder temperature is elevated above its  $T_g$ ,  
43 although the temperature above  $T_g$  does depend on the material,  $T_g$  definition (onset or  
44 midpoint) and test method used (Murti et al., 2006; Paterson et al., 2005; Foster et al.,  
45 2006). At these temperatures, powders develop viscous behaviour that may give rise to  
46 stickiness and caking. They may also flow into each other and form sinter bridges that  
47 give rise to very strong cakes (Palzer, 2005). Moisture content has a big influence on  $T_g$   
48 with higher moistures leading to lower  $T_g$ . Consequently, caking of powder particles  
49 composed mainly of amorphous substances is strongly dependent on the relative

50 humidity of the surrounding air and temperature. Crystallisation may also occur if the  
51 powder temperature is greater than its  $T_g$ , especially for smaller molecules such as  
52 lactose whereby the molecules have sufficient mobility to initiate crystallisation (Jouppila  
53 and Roos, 1994; Jouppila et al., 1997; Roos, 2002; Lai and Schmidt, 1990). This will also  
54 impact on the caking behaviour and cake strength of a powder.

55 Food powder mixes can contain a variety of component powders and may cake when  
56 exposed to higher relative humidities or when compacted. The caking behaviour is often  
57 attributable to one or a small number of powders that become sticky and cause the mix to  
58 cake. Consequently, the susceptibility to caking will depend on the stickiness and fraction  
59 of “sticky” powder present and how it interacts with the other powders. There is a  
60 significant amount of work presented in the literature on the flowability and caking  
61 behaviour of individual powders. However, there is very little work reported on the  
62 caking of powder mixes. The focus on powder mixes is important, as many powder  
63 ingredients are formulated and supplied as a mix of different powders. The aim of this  
64 work is to investigate the caking behaviour of food powder mixes. In particular, how  
65 powder fractions and powder properties coupled with time and handling conditions  
66 influence the caking behaviours of powder mixes. This work focused on simple binary  
67 mixes consisting of a “sticky” powder and a “non-sticky” powder. The “sticky” powders  
68 were whey permeate and maltodextrin DE21; the “non-sticky” powders were salt, flour  
69 and paprika. The study investigated how the fraction of “sticky” powder, its stickiness  
70 and interaction with “non-sticky” powders influenced the caking behaviour of the binary  
71 powder mixes. A novel force-displacement tester was used to measure cake strength  
72 (Fitzpatrick et al., 2008). This was supplemented by the use of digital microscopy to

73 visually assess the adhesion of two powder particles in contact, similar to work reported  
74 by Feeney and Fitzpatrick (2011).

75

## 76 **2. Materials and methods**

### 77 **2.1 Powders**

78 A 25 kg bag of commercial spray-dried maltodextrin DE 21 (Glucidex® 21) was  
79 obtained from Roquette Frères, Lestrem, France. A 25 kg bag of commercial spray-dried  
80 whey permeate powder was obtained from Kerry Ingredients, Ireland. A wheat flour  
81 (Odlums) and sodium chloride salt (Saxo) was obtained from a local supermarket, and a  
82 paprika powder was obtained from a local spice powder supplier. Sodium chloride was  
83 obtained from Sigma-Aldrich Fluka for controlling relative humidity.

84

### 85 **2.2 Powder properties**

86 Moisture content of powders (% w/w) was measured using an infra-red moisture  
87 analyser (Sartorius MA 150). The median ( $d_{50}$ ) of a volume particle size distribution was  
88 measured by laser diffraction using the Malvern Mastersizer MSS with powder feeder  
89 unit. Powder tapped bulk density was measured using an Engelsmann model A.-G.  
90 mechanical tapping device, where the volume of a given mass of powder was measured  
91 after 400 taps. The moisture content, particle size and bulk density of the powders tested  
92 are provided in Table 1.

93 The whey permeate and maltodextrin powders were chosen as “sticky” powders  
94 because they have amorphous components that when subjected to 76% relative humidity  
95 over time will sorb sufficient moisture to become sticky. The three “non-sticky” powders

96 (salt, flour and paprika) were chosen because they have different properties. The salt is a  
97 crystalline material, while the others are not. Table 1 shows that there is a major variation  
98 in moisture content with salt having a very low value of 0.06%, flour having a high value  
99 of over 10% and paprika having an in between value of nearly 6%. Table 1 also shows  
100 significant variations in particle size and bulk density.

101

### 102 **2.3 Measurement of powder cake strength**

103 An empirical tester for quantitatively measuring an index of cake strength was used  
104 (Fitzpatrick et al., 2008). It consisted of placing around 20 g of powder into a cylindrical  
105 aluminium dish which had a circular hole exactly in the centre of the dish with  
106 dimensions illustrated in Fig. 1a. A layer of aluminium foil was taped to the bottom of the  
107 dish to cover the hole, preventing powder falling through and to prevent exposure to  
108 atmosphere through the hole. The powder was spread out across the dish using a levelling  
109 device to give a thin powder layer of about 7 mm. Samples were then exposed to a  
110 relative humidity of 76% RH at 20°C over time to investigate how these conditions  
111 influence the cake strength of the powders. The relative humidity was achieved by  
112 placing a dish containing powder into a glass kilner jar (Fig. 1b), containing a saturated  
113 sodium chloride solution to obtain 76% RH, which was then sealed.

114 Following exposure, a dish was removed from the kilner jar, the foil was removed  
115 from beneath the aluminium dish and the dish was centred below a rod attached to a TA  
116 HD Plus Texture Analyser (Stable Microsystems, UK). The rod had a diameter of 5 mm  
117 and was initially moved downwards to just above the top of the caked powder. The rod  
118 was then moved downward through the caked powder at a constant speed of 30 mm/min

119 and the force versus displacement was measured using the TA Texture Analyser as the  
120 rod moved through the cake. As the rod engaged the surface of the cake, the force  
121 increased to a maximum and then gradually reduced as the rod continued to push a plug  
122 of caked powder through the hole in the centre of the dish. The peak force measured was  
123 defined as the cake strength. The water content of the caked sample was then measured  
124 by taking three samples of caked powder and measuring the water content.

125

#### 126 **2.4 Visual assessment of powder particle adhesion using microscopy**

127 A light microscope capable of taking digital images (Bresser LCD Micro 40X-1600X)  
128 was used to take photographs of two powder particles in contact with each other when  
129 exposed to different relative humidities (Feeney and Fitzpatrick, 2011). Two powder  
130 particles were placed in contact with each other inside a transparent Petri dish. An open  
131 aluminium dish containing a saturated NaCl salt solution was also placed inside the Petri  
132 dish (to produce 76% relative humidity). The Petri dish was then sealed using a parafilm  
133 tape. Photographs were taken of the particles over time using the microscope to visually  
134 observe any changes in particle shape and formation of any bridges between the particles.

135

#### 136 **2.5 Experimental trials**

137 The “sticky” powders were exposed to 76% RH over time to measure cake strength  
138 and moisture content over time. These data were used to investigate the caking behaviour  
139 and to identify an exposure time required to attain a high cake strength. These exposure  
140 times would then be used subsequently in the binary mixing trials with the “non-sticky”  
141 powders. The chosen exposure times for whey permeate and maltodextrin mixes were

142 chosen to be 8 hours and 6 days, respectively, and this is outlined in more detail in  
143 section 3. The “non-sticky” powders were also exposed to these time durations to ensure  
144 that the powders did not cake.

145 At the selected exposure times, binary powder mixes containing a “sticky” and “non-  
146 sticky” powder were formulated on a % “sticky” powder weight per total powder weight  
147 basis. These were formulated at compositions of 20%, 40%, 60%, 80% and 90% “sticky”  
148 powder. The mixing was done rapidly to prevent moisture sorption and each mix was  
149 placed in an aluminium dish and placed inside a kilner jar for the chosen exposure time,  
150 as described in section 2.3, after which cake strength and moisture content were  
151 measured. The tests were done in duplicate and the measured values are presented in the  
152 figures as error bars around the average values. Complementary visual assessment trials  
153 were conducted where photographs were taken over time of two particles in contact, as  
154 outlined in section 2.4.

155

### 156 **3. Results and discussion**

#### 157 **3.1 Caking behaviour of the sticky and non-sticky powders**

158 The evolution of cake strength and moisture content over time for the “sticky”  
159 powders, whey permeate (WP) and maltodextrin (MD), is presented in Fig. 2. The WP  
160 attained a maximum cake strength of about 34 N after about 10 hour exposure and the  
161 moisture content increased from an initial moisture content of 1.9% to about 3.7%. After  
162 10 hour exposure, cake strength decreased down to about 10 N after 24 hour exposure.  
163 The moisture content showed a decrease to about 3.2% from 10 to 14 hour exposure, but  
164 was then followed by an increase to around 5.1% after 24 hour exposure. The decrease is

165 indicative of some amorphous lactose crystallisation because crystalline lactose binds  
166 little water at the exposure conditions. The caking of WP is most likely due to stickiness  
167 associated with amorphous lactose absorbing moisture and its glass transition temperature  
168 (T<sub>g</sub>) being reduced below the powder temperature of 20 °C. However, at the T<sub>g</sub> of 20 °C,  
169 the equilibrium moisture content of amorphous lactose is about 7% (Roos, 2002). This is  
170 much greater than any of the moisture contents measured during the 24-hour test. The  
171 reason for this is possibly due to the WP powder containing a significant amount of  
172 lactose in the crystalline state, thus the amorphous lactose present is only a fraction of the  
173 lactose and the moisture content of the amorphous content is potentially much higher  
174 giving rise to stickiness.

175 Amorphous powder particles at temperatures above their T<sub>g</sub> are no longer glassy solids  
176 and attain viscous properties which enable them to change shape and flow into each other  
177 forming sinter bridges between particles (Descamps et al., 2013; Palzer, 2005).  
178 Photographs were taken of two WP particles in contact over time when exposed to 76%  
179 RH, to observe if any bridging between particles or change in particle shape was taking  
180 place. This is illustrated in Figure 3a, which shows no significant change in particle shape  
181 or formation of sinter bridges. These results could be due to only a fraction of the lactose  
182 being in amorphous state giving rise to stickiness but the remaining lactose being in  
183 crystalline state along with other components present preventing flow and deformation of  
184 the WP particles.

185 The MD powder formed a much stronger cake of around 190 N and it took a lot longer  
186 time of about 5 to 6 days. There was a major increase in the moisture content from an  
187 initial moisture content of about 3.3% up to 17% after 7-day exposure. MD is a spray-

188 dried powder and is mainly in the amorphous form, thus its stickiness and strong cake  
189 formation is most likely due its glass transition temperature being reduced below the  
190 powder temperature (Descamps et al., 2013). At the T<sub>g</sub> of 20 °C, the equilibrium  
191 moisture content of amorphous maltodextrin DE21 is about 10.7% (Descamps et al.,  
192 2013). At the measured high cake strengths on days 4 to day 7, the moisture content  
193 increased from 10 to 17%, which is within or above that at a T<sub>g</sub> of 20 °C. Photographs  
194 were also taken of two MD particles in contact over time when exposed to 76% RH, to  
195 observe if any bridging between particles or change in particle shape was taking place.  
196 This is illustrated in Fig. 3a, where particle deformation and sinter bridging were  
197 observed and this gave rise to the very strong cake strengths measured.

198 As highlighted above, a major reason for conducting trials on the “sticky” powders  
199 alone was to identify an exposure time required to attain a high cake strength. From Figs.  
200 2a and 2b, exposure times of 8 hours and 6 days were chosen for WP and MD,  
201 respectively. Repeatability tests were then carried out to ensure that there was no large  
202 variability in cake strength and moisture content at these times. Five replicates were  
203 conducted at these times and the mean and standard deviations are provided in Table 2,  
204 which show good repeatability at these exposure times.

205 The cake strengths and moisture contents of the “non-sticky” powders (salt, paprika  
206 and flour) were also measured when exposed to 76% RH over a 24-hour period and  
207 results are presented in Table 3. The powders did not cake over the 24-hour exposure  
208 time with no or very low strengths measured, the highest being 0.6 N for the paprika  
209 powder at 24-hour exposure (At strengths less than the 1 N, the powder is still a powder  
210 rather than a cake and has sufficient strength to span or form a cohesive bridge across the

211 hole in the bottom of the aluminium dish). This is to ensure that they remain non-sticky  
212 during testing. These powders also did not deform or change shape, as illustrated by the  
213 visual assessment in Fig. 3b.

214

### 215 **3.2 Caking behaviour of binary mixes containing whey permeate powder**

216 The effect of mixture composition on cake strength and moisture content, after 8 hour  
217 exposure to 76% RH at 20 °C, is presented in Fig. 4. The moisture content data did not  
218 display any unusual behaviour as the moisture contents of the mixes with higher whey  
219 permeate powder fraction moved progressively towards the moisture content of whey  
220 permeate powder, as illustrated in Fig. 4a. As expected, increasing the “sticky” whey  
221 permeate powder fraction does impact on the caking behaviour of the mixes, but it is not  
222 a linear relationship and it does depend on the “non-sticky” powder, as illustrated in Fig.  
223 4b. These results show that at a WP powder fraction of 20%, there was no caking with  
224 measured cake strengths being very low at less than 1 N. At 40% WP fraction, weak  
225 cakes formed with cake strengths of about 2.5 N for both flour and paprika and 7 N for  
226 salt. The net result from these observations is that caking did not occur up to 20%  
227 fraction of the “sticky” WP powder and a weak cake started to form somewhere between  
228 20 and 40% WP powder fraction.

229 Fig. 4b shows that the caking behaviour varies depending on the “non-sticky” powder  
230 in the mixes, with salt forming the strongest cakes and paprika forming the weakest. For  
231 example, at 80% WP powder fraction, the cake strengths of the mixes as a % of the cake  
232 strength of 100% WP were 72% (salt), 64% (flour) and 20% (paprika). Photographs are  
233 presented in Fig. 5 of a “sticky” and “non-sticky” powder particles in contact when

234 exposed to 76% RH. These show no noticeable changes in particle shape or contact area  
235 between particles, thus no high viscosity flow or bridging was observed. This is  
236 somewhat expected considering the photographs presented in Fig. 3. Consequently, the  
237 caking is most likely due to stickiness being developed by the amorphous lactose on the  
238 surface of the whey permeate powder particles. There are no obvious reasons for the  
239 variation in cake strength between the mixes. It might be related to the different moisture  
240 content of the mixes and the intrinsic surface chemistry of different powders giving rise  
241 to variations in attractive forces. It might be influenced by powder particle contacts  
242 within the powder bed, which in-turn is influenced by particle sizes, shapes and  
243 flowability.

244

### 245 **3.3 Caking behaviour of binary mixes containing maltodextrin powder**

246 The effect of increasing the “sticky” MD powder fraction on the caking behaviour of  
247 the mixes, after 6 day exposure to 76% RH at 20 °C, is presented in Fig. 6a. This is  
248 somewhat similar to the WP presented in Fig. 4b, showing a non-linear relationship. At  
249 6-day exposure, the moisture contents of the “non-sticky” powders are all relatively high  
250 as presented in Table 3 and being about 14.3% for MD powder. For the mixes, the  
251 moisture contents behaved similarly to WP, as illustrated in Fig. 6b, with the moisture  
252 contents approaching that of MD at higher MD contents. The cake strength results show  
253 that at a MD content of 20%, there was no or little caking with measured cake strengths  
254 being less than 1 N for the salt (0.3N) and paprika (0.6 N), and being a little greater at 2N  
255 for the flour mix. This is somewhat similar to WP. At 40% MD fraction, cakes formed  
256 with cake strengths of about 10 N and 6 N for flour and paprika, respectively, however

257 the salt still did not cake, having a measured cake strength of 0.4 N which is less than 1  
258 N.

259 The cake strengths of the MD/flour and MD/paprika mixes were greater than their WP  
260 counterpart mixes (Table 4), and this would be expected considering the large cake  
261 strength developed by 100% MD. However, the cake strengths of the mixes as a % of the  
262 100% “sticky” powder were lower for the MD mixes, in particular for the salt and flour  
263 mixes. For example, the 80% MD fractions were only 8% for salt and 16% for paprika,  
264 which is much lower than their 80% WP mixes. For the WP mixes, the salt mixes formed  
265 the strongest cakes but formed the weakest cakes for the MD mixes. In fact, the MD/salt  
266 mixes produced weaker cakes than the WP/salt mixes.

267 Visual assessment of two particles in contact at 76% RH was undertaken, and the  
268 resulting photographs are presented in Fig. 7. Changes were expected because the MD  
269 particles did deform in Fig. 3. A major change occurred over time with the MD / salt  
270 particles. The MD deformed readily and flowed into the salt particle and eventually  
271 engulfed it, with the salt particle appearing to gradually dissolve within it. This liquid like  
272 behaviour may explain the weak cake strengths developed by the MD/salt mixes. It may  
273 also explain why the cake strengths of MD/salt mixes were much lower than the WP/salt  
274 mixes. For the MD / paprika particle contact, Fig. 7 shows the MD deforming over time  
275 and separating from the paprika particle. For the MD/flour, Fig. 7 shows 2 trials which  
276 show different phenomena. One MD/flour set of photos shows the MD deforming and  
277 increasing its association or contact with the flour, while the next set of MD/flour photos  
278 shows the MD deforming and detaching from the flour particle, much like the paprika.  
279 This suggests that when the MD deforms it may either coalesce more strongly with the

280 flour or paprika or separate from them, and this is possibly influenced by the initial  
281 shape, size and contact area of the particles. This behaviour may in-part explain the  
282 greatly reduced cake strengths of the flour and paprika mixes in comparison to the 100%  
283 MD powder, whereby some of the particle contacts may be lost in a powder bed due to  
284 separation caused by the deformation of MD. However, a major reason for the reduction  
285 in cake strength is most likely due to the reduction in the amount of strong sinter bridging  
286 between the MD particles themselves, due to there being less MD in a mix and  
287 consequently less MD/MD particle contact.

288

### 289 **3.4 Caking behaviour of binary mixes containing MD and WP powders**

290 A final set of trials were undertaken for binary mixes containing the two “sticky”  
291 powders (MD and WP). Mixes were formulated at 20%, 40% 60% and 80% MD powder  
292 fractions and exposed to 76% RH for 6 days. At 6-day exposure, the moisture content of  
293 WP and MD were about 12% and 14.3%, respectively. The moisture contents of the  
294 mixes were within this range. The cake strength of the MD/WP mixes is presented in Fig.  
295 8a, along with those for the other MD mixes for comparison. The cake strength behaviour  
296 of the MD/WP mixes is somewhat similar to the other MD mixes. There was little or no  
297 caking at lower MD fractions up to 40% MD, followed by much stronger cakes at 60%  
298 and 80% MD. It might initially be surprising to have had little or no caking up to 40%  
299 MD considering that both powders are termed “sticky”, however it must be kept in mind  
300 that the exposure time was 6 days and the cake strength of WP significantly decreases  
301 after about 10 hours and is very low at about 5 N after 6 days. Thus, at 6-day exposure,  
302 the WP is behaving like a “non-sticky” powder, most likely because much of its

303 amorphous lactose has crystallised. Consequently, this may explain why MD/WP is  
304 behaving somewhat similarly to the other MD/"non-sticky" mixes at lower MD powder  
305 fractions.

306 At 60% and 80% MD, the MD/WP mix developed much stronger cake strengths than  
307 the other MD mixes, as illustrated in Fig. 8a. This may in-part be explained by the visual  
308 assessment of the MD and WP powder particles in contact presented in Fig. 8b. Here, the  
309 MD particle deforms over time, as expected, and the WP particle does not. Fig. 8b shows  
310 the MD particle flowing onto the WP particle over time, resulting in a large bridge  
311 between the 2 particles. The existence of this type of bridge may explain the higher cake  
312 strengths obtained at 60% and 80% MD in the MD/WP mixes as compared to the other  
313 MD mixes.

314

#### 315 **4. Conclusions**

316 The application of a force-displacement test for measuring cake strength coupled with  
317 visual assessment of two particles in contact is a useful approach for investigating the  
318 caking behaviour of powders. The two "sticky" powders used in this study behaved  
319 somewhat differently, insofar as the WP became sticky but did not deform, while the MD  
320 did deform which enabled it form sinter bridges between MD particles. Consequently, the  
321 MD powder formed much a stronger cake than the WP powder.

322 In relation to the "sticky" / "non-sticky" powder mixes, a "sticky" powder mass  
323 fraction of at least 20% was required to initiate caking and formation of weak cakes. As  
324 expected, increasing percentage "sticky" powder fraction above the initial caking  
325 percentage resulted in progressively stronger cakes. For the MD mixes, the cake strengths

326 of the flour and paprika were stronger than their corresponding WP mixes, which was  
327 expected as the MD inherently forms stronger cakes. However, cake strengths developed  
328 as a percentage of 100% “sticky” powder were less for the MD mixes, thus the “non-  
329 sticky” powders had a greater impact on reducing the cake strength of the more “sticky”  
330 MD powder. This is most likely due to a reduction in the number of contacts between  
331 MD particles and thus a reduction in the amount of the strong MD / MD sinter bridges.

332 The particular “non-sticky” powder had an influence on the cake strength of the mix.  
333 For example, the salt powder displayed very different behaviour for the WP and MD  
334 mixes, forming the strongest cakes for WP mixes and the weakest for MD mixes. The  
335 visual assessment of two particles in contact contributed to trying to interpret these  
336 differences, as the caking behaviour is influenced by the “sticky” powders ability to  
337 deform and flow, which can be captured using a digital microscope.

338

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## LIST OF FIGURES

**Fig. 1.** (a) Aluminium dish used in force-displacement cake strength determination (with central hole and foil cover underneath to prevent powder falling through). (b) kilner jars used in the control of relative humidity using a saturated NaCl solution.

**Fig. 2.** Evolution of powder cake strength and moisture content over time at 76% RH (20 °C): (a) whey permeate; (b) maltodextrin.

**Fig. 3.** Photographs of 2 powder particles in contact over time when exposed to 76% RH (20 °C): (a) “sticky” powders; (b) “non-sticky” powders.

**Fig. 4.** Effect of whey permeate powder fraction on the caking of powder mixes (8 hour exposure to 76% RH at 20 °C).

**Fig. 5.** Photographs of whey permeate powder particle [particle at the bottom] in contact with a non sticky powder particle when exposed to 76% RH (20 °C) over time: (a) salt; (b) flour; (c) paprika.

**Fig. 6.** Effect of maltodextrin powder fraction on the caking of powder mixes (6 day exposure to 76% RH at 20 °C).

**Fig. 7.** Photographs of maltodextrin powder particle [particle on the left] in contact with a non sticky powder particle when exposed to 76% RH (20 °C) over time: (a) salt; (b) flour; (c) paprika.

**Fig. 8.** Maltodextrin / whey permeate powder mixes (a) cake strength; (b) visual assessment [maltodextrin particle is on the left].

Fig. 1.

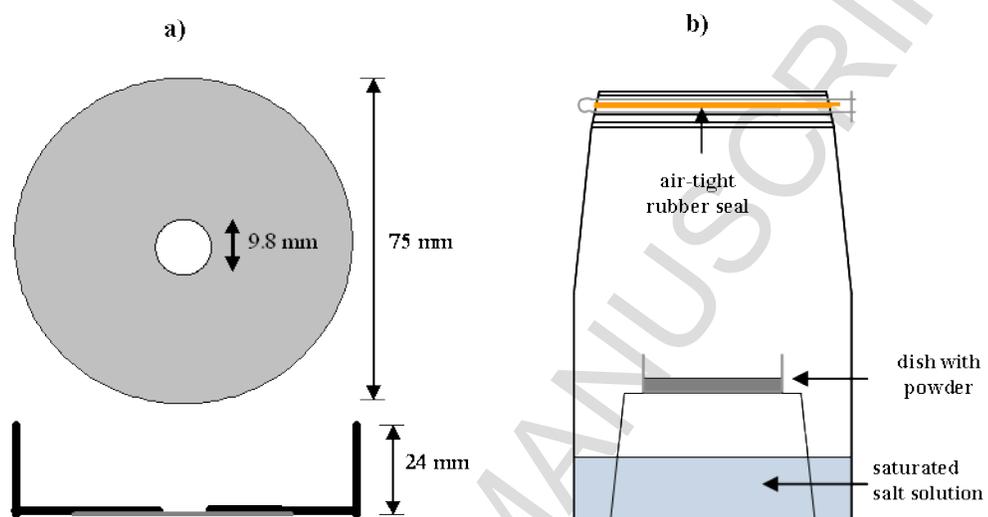


Fig. 2.

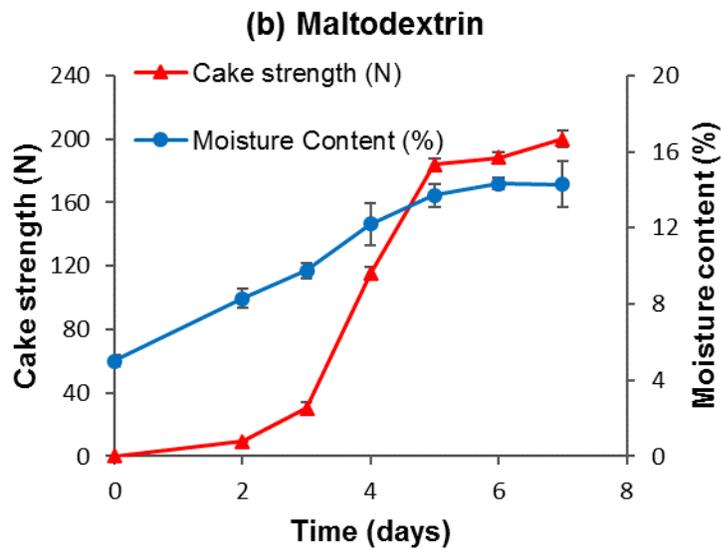
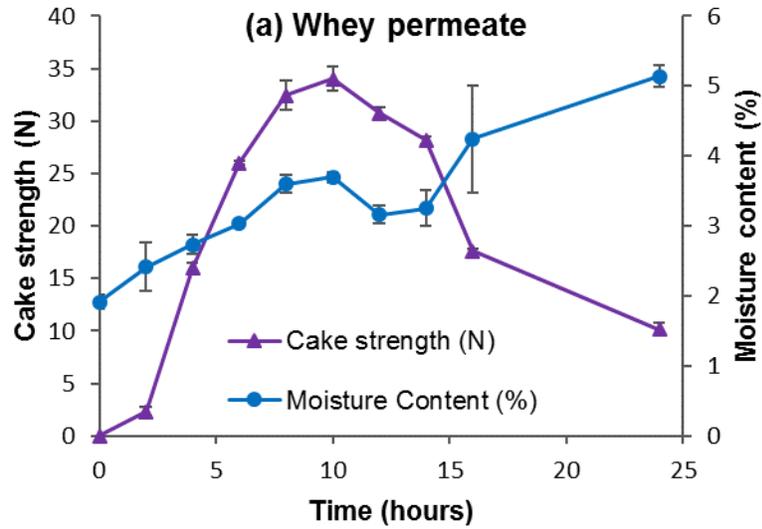




Fig. 4.

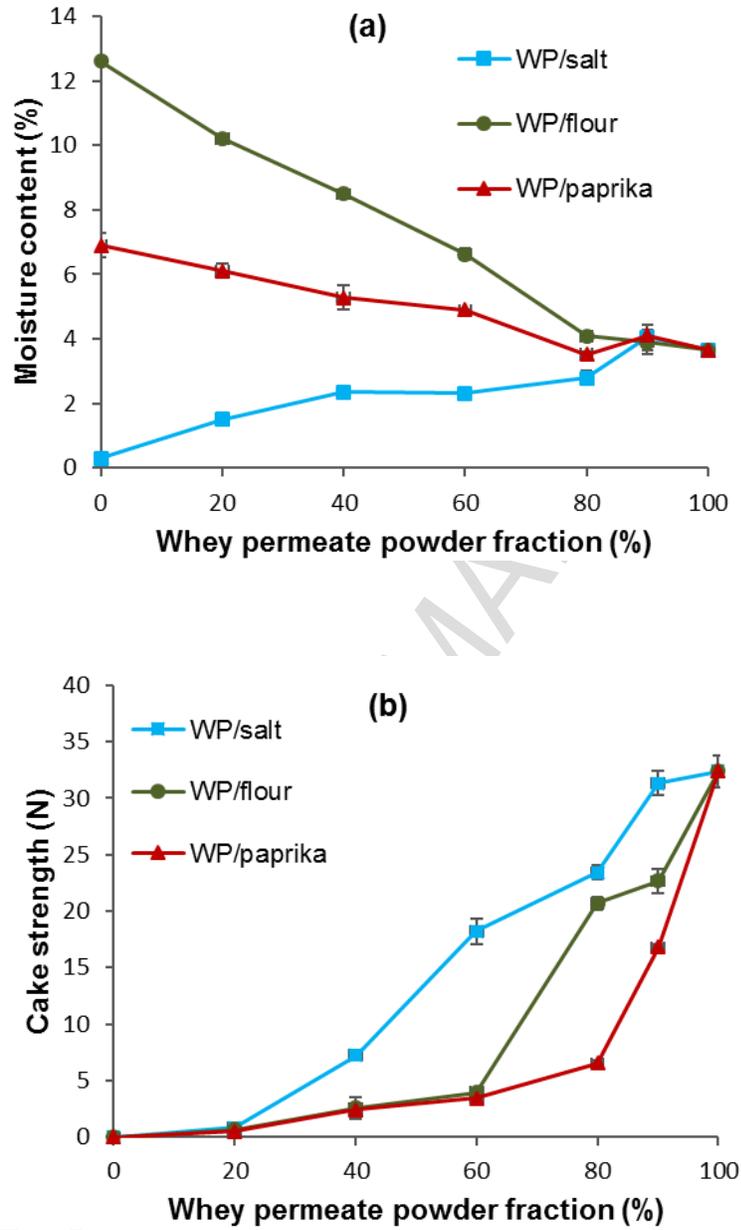


Fig. 5.

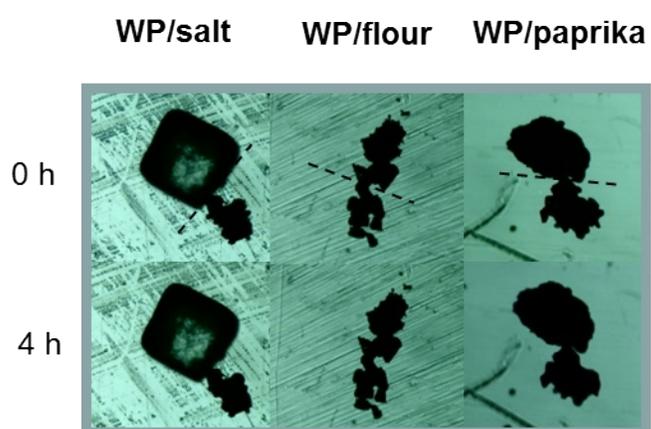


Fig. 6.

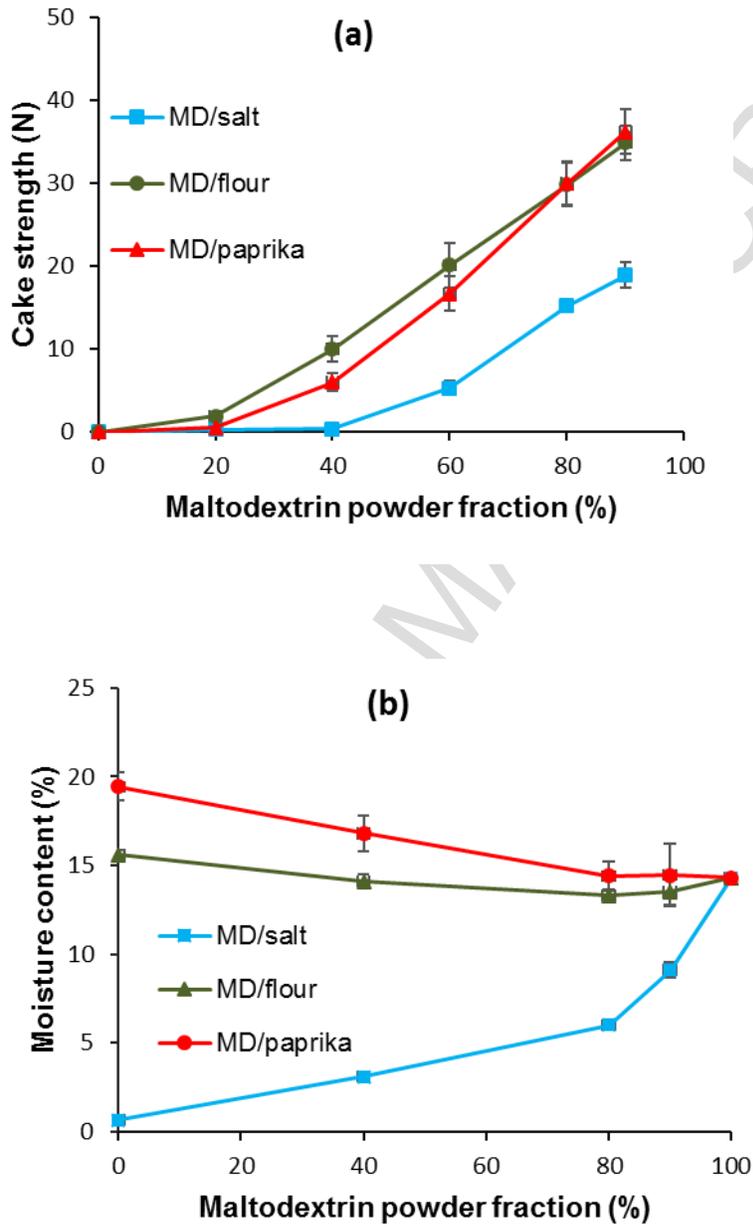


Fig. 7.

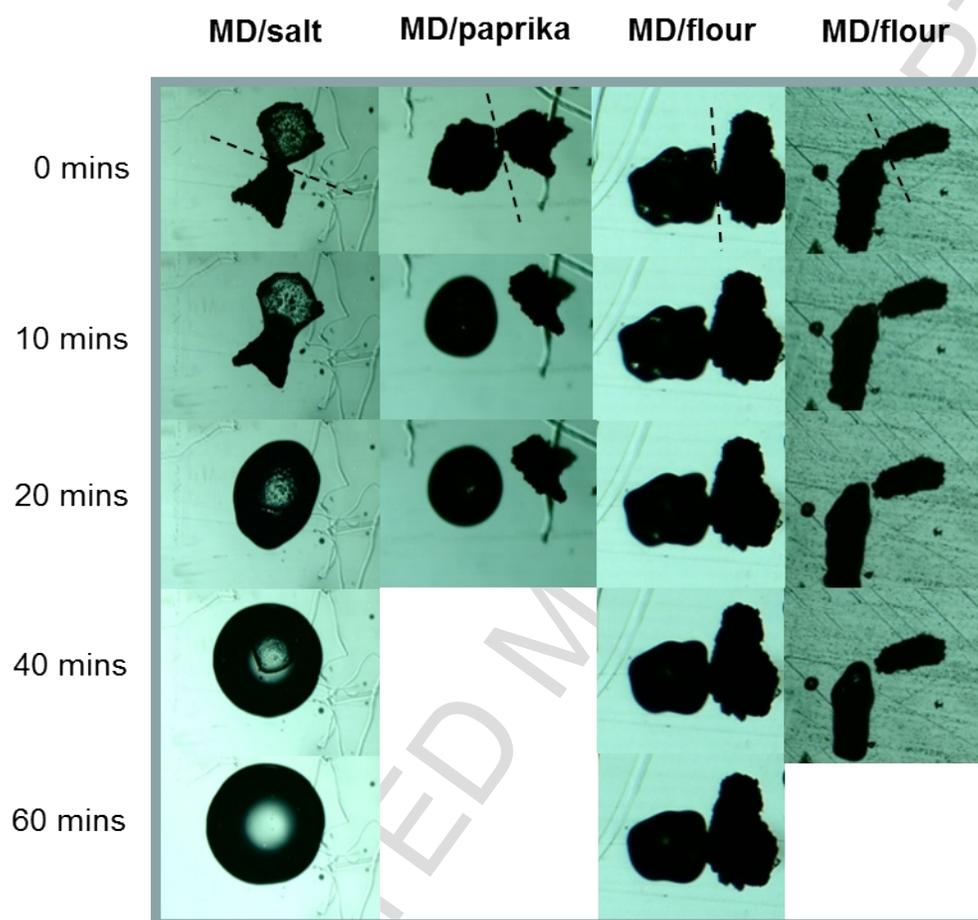
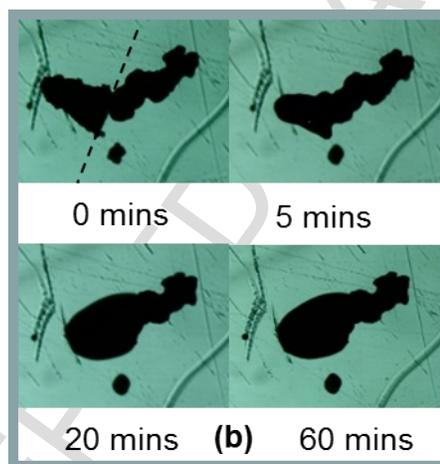
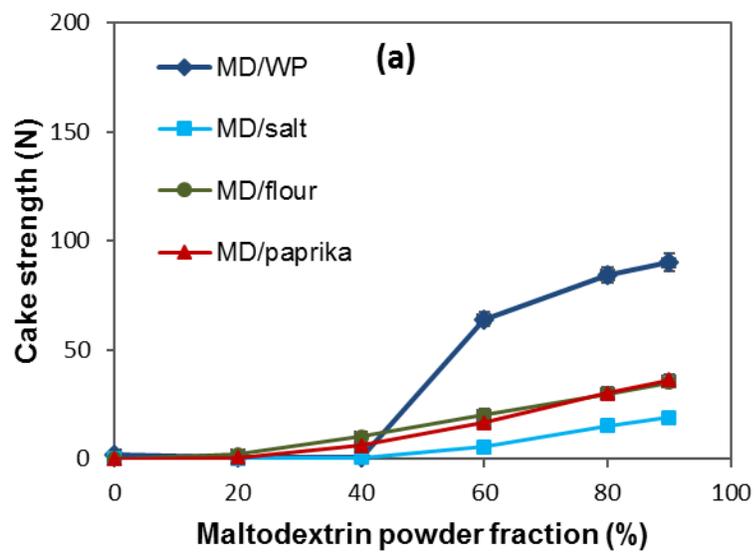


Fig. 8.



## TABLES

**Table 1.** Powder moisture content, particle size and tapped bulk density

Powder	Moisture content (%)	Particle size $d_{50}$ (microns)	Bulk density ( $\text{kg L}^{-1}$ )
Whey permeate	1.9	92	0.93
Maltodextrin	3.3	110	0.31
Flour	10.6	65	0.77
Paprika	5.8	190	0.53
Salt	0.06	280	1.44

**Table 2.** Repeatability assessment of cake strength and moisture contents measurements [5 replicates].

	Whey permeate		Maltodextrin	
	Mean	Standard deviation	Mean	Standard deviation
Cake strength (N)	32.4	1.4	188	3.7
Moisture content (%)	3.65	0.13	14.3	0.31

**Table 3.** Cake strength and moisture content of “non-sticky” powders when exposed to 76% relative humidity (20 °C) over time.

	salt	flour	paprika
<u>Cake strength (N)</u>			
<u>Time</u>			
0 h	0	0	0
4 h	0	0	0.1
8 h	0	0	0.2
24 h	0.07	0.06	0.6
6 day	0.14	0.17	1.1
<u>Moisture content (%)</u>			
<u>Time</u>			
0 h	0.06	10.6	5.8
4 h	0.15	11.7	6.2
8 h	0.29	12.6	6.9
24 h	0.61	12.7	9.3
6 day	9.1	12.8	13.8

**Table 4.** Cake strengths (N) of whey permeate (WP) and maltodextrin (MD) powder mixes when exposed to 76% relative humidity (20 °C) [exposure time: 8 h for WP; 6 days for MD].

% “sticky” powder	<u>Salt mixes</u>		<u>Flour mixes</u>		<u>Paprika mixes</u>	
	WP	MD	WP	MD	WP	MD
0	0	0	0	0	0	0
20	0.8	0.3	0.7	1.9	0.5	0.6
40	7.2	0.4	2.6	10.0	2.4	6.0
60	18.2	5.3	4.0	20.1	3.4	16.7
80	23.4	15.2	20.7	29.8	6.5	30.0
90	31.3	18.9	22.7	34.9	16.8	36.2
100	32.4	188	32.4	188	32.4	188