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Characterization of the viscoelasticity of pharmaceutical tablets using impulse excitation technique

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Abstract

Pharmaceutical tablets can be produced on different kinds of presses that may have very different compaction kinematics. Strain rate sensitivity (SRS) is thus an important property for the powders used to produce pharmaceutical tablets. Viscoelasticity is one of the aspects of the SRS and can be sometimes difficult to characterize. In this work, impulse excitation technique was used as an easy-to-implement method for characterizing viscoelasticity using the fact that this property induces damping which can be detected on resonance spectra as peak enlargements. A damping ratio, related to the first flexural vibration mode, was determined on impulse excitation frequency spectra using the half-power bandwidth method on tablets made with different products. This method made it possible to obtain reproducible results for the damping ratio. As viscoelasticity is not the only phenomena that can promote damping, tests were made in order to assess the influence of other parameters: viscoplasticity, porosity and tablet dimensions. Results indicated that the influence of these phenomena could be considered as negligible.

25 Finally, the damping ratios determined were in good accordance with the known
26 viscoelastic behavior of the studied products. This made it possible to confirm that impact
27 resonance is an easy and quick way to characterize the viscoelastic nature of
28 pharmaceutical tablets.

29 **Keywords:** tablet, compression, viscoelasticity, damping, impact resonance, Strain rate
30 sensitivity

31 **1 Introduction**

32 Pharmaceutical tablets are produced, at the industrial scale, using die compaction on
33 large rotary presses. One of the specificity of the die compaction process in the
34 pharmaceutical field, compared to other fields such as powder metallurgy or ceramics, is
35 the very short time during which the stresses are applied to the product. The compaction
36 event lasts, indeed, only a few milliseconds, especially on the largest rotary presses, and
37 punch speed can be up to around $1 \text{ m}\cdot\text{s}^{-1}$. As a consequence, time-dependent phenomena
38 occurring during compaction play an important role in the final tablet properties. The
39 dependency of the tablet properties on the compaction speed is generally called strain
40 rate sensitivity (SRS) (Alderborn, 2001; Armstrong, 1989). SRS is of particular importance
41 during scale-up because there can be a large difference between the kinematic of
42 compaction of a small development press and the one of a large production press.

43 Even if the dynamic effects occurring during compaction are often described by the single
44 concept of SRS, it is important to note that several different phenomena can be involved,
45 like speed-dependent friction (Desbois et al., 2019), viscoplasticity, viscoelasticity (Çelik
46 and Aulton, 1996; Katz and Buckner, 2013; Malamataris and Rees, 1993; Morehead,

47 1992; Rehula et al., 2012; Van Der Voort Maarschalk et al., 1996) or air entrapment
48 (Casahoursat et al., 1988; Zavaliangos et al., 2017). These different phenomena may not
49 influence in the same way the final tablet properties and it is thus important to develop
50 characterization methods that are suited to study independently each of these
51 phenomena. The present work is focused on the case of viscoelasticity.

52 A product is viscoelastic if its elastic (recoverable) deformations are time-dependent
53 (Alderborn and Nyström, 1996; Vincent, 2012). Several methodologies have been
54 proposed in the literature to characterize the viscoelastic nature of pharmaceutical tablets.
55 Some of these methodologies are applied to the tablet after its ejection from the die like
56 dynamical mechanical analysis or relaxation tests (Ascani et al., 2019; Çelik and Aulton,
57 1996; Hancock et al., 2001; Radebaugh et al., 1989) and some are developed directly on
58 the tablet press before ejection (Casahoursat et al., 1988; Desbois et al., 2020; Rees and
59 Rue, 1978; Rehula et al., 2012; Rippie and Danielson, 1981).

60 One of the characteristics of viscoelasticity is that it acts as a damping factor during the
61 vibrations of a solid. It is thus also possible to study viscoelasticity by studying these
62 damping phenomena. One way can be to study the damping of an elastic wave (e.g.
63 ultrasonic wave) during its propagation in the tablet (Saeedi Vahdat et al., 2013). Another
64 way can be to acquire the spectra of the natural frequencies of the solid and to
65 characterize the shape of the peaks. The presence of damping in a solid promotes an
66 enlargement of the vibration peaks corresponding to natural frequencies. This
67 enlargement can be measured for example using the half-power bandwidth method
68 (Meirovitch, 2010). From the experimental point of view, several techniques can be used
69 to measure the natural vibrations of a solid to characterize the damping like resonant

70 ultrasound spectroscopy (Bernard et al., 2014; Lee et al., 2000) or impulse excitation
71 technique (Popov and Shitikova, 2020).

72 Impulse excitation technique was recently introduced in the pharmaceutical field (Mazel
73 and Tchoreloff, 2020) and proved to be an easy and quick methodology to characterize
74 the elastic behavior of pharmaceutical tablet including its anisotropy (Meynard et al.,
75 2021). The goal of the present work is to extend the use of this methodology for the
76 characterization of the viscoelastic behavior of pharmaceutical tablets by studying tablet
77 damping behavior with the half-power band method. For this purpose, the applicability of
78 the half-power bandwidth method for pharmaceutical tablets was investigated in order to
79 determine the convenient conditions to evaluate tablet modal damping ratios. Finally, the
80 validation of this method to characterize tablet viscoelastic behaviour was realized.

81

82 **2 Theoretical considerations**

83 **2.1 Definition of damping**

84 Vibrations require energy. In the case of free systems, energy is given to the system when
85 an external force sets the system in motion. When those vibrations are undamped, this
86 energy is transformed, without dissipation, from potential to kinetic energy and vice versa.
87 The amplitude of vibrations is thus constant for an infinite period of time. The intrinsic
88 characteristics of an undamped system vibrating freely after external perturbations are: a)
89 the displacement patterns associated with its harmonic vibrations (called 'mode shapes')
90 and b) the given specific oscillation frequency at which the system vibrates (called 'natural
91 frequencies'). However, in real-life vibrating systems, energy gets dissipated continuously

92 in different forms over time. The amplitude of vibrations gradually decreases and goes to
93 zero over time.

94 A common way to model damping is to assume proportional viscous damping using
95 Rayleigh model (Strutt, 2011). The equation of motion for a viscously damped vibrating
96 freedom system in modal coordinates reads:

$$97 \quad \ddot{y}(t) + 2\zeta_i\omega_i\dot{y}(t) - \omega_i^2y(t) = 0 \quad (2)$$

98 Where y , \dot{y} and \ddot{y} are the displacement, velocity and acceleration vectors and the
99 parameters ω_i and ζ_i are respectively the angular natural frequency and modal damping
100 ratio related to each classical mode shape i . Damping ratios ζ_i are modal parameters
101 related to the damping behaviour of each mode shape i of the tablet studied.

102 **2.2 The half-power bandwidth method**

103 In this work, we chose to measure the damping ratio ζ_i related to a given mode i on the
104 amplitude-frequency curve at resonance (Bachmann et al., 1994) using the half-power
105 bandwidth method. This method is commonly used in different fields, e.g. in the
106 characterization of building structures (Papagiannopoulos and Hatzigeorgiou, 2011; Shi
107 et al., 2012) or biological materials (Mc Donnell et al., 2009; Veltri et al., 2007).

108 The half-power bandwidth method considers a symmetrical response curve, light damping
109 ($\zeta_i < 1/2\sqrt{2}$), no effect of neighbouring modes on the analysed mode and the knowledge
110 of impact of the excitation signal on the frequency response (Beards, 1996; Silva, 2006).

111 The modal damping ratio related to a mode i was defined as:

$$112 \quad \zeta_i = \frac{\Delta\omega}{2\omega_i}$$

113 where $\Delta\omega$ is the frequency bandwidth related to the half-power amplitude $y_{max}/\sqrt{2}$. Note
114 that there are other parameters that evaluate damping such as the loss factors Q_i and that
115 there are all mathematically related, e.g. $Q_i = 1/(2\zeta_i)$. Figure 1 shows an illustration on a
116 peak of the evaluation of the damping ratio using the half power bandwidth method.

117 The more damped a mode is, the faster the decay of its vibrations is when set in motion
118 which leads to wider peaks on the frequency spectra. Thus, for a given shape mode, an
119 increase of its width is directly related to an increase of its damping ratio.

120

121 **3 Materials and methods**

122 **3.1 Powders**

123 Four classical pharmaceutical excipients for direct compression were used in this study:
124 lactose monohydrate “MLac” (Excipress GR150, ArmorPharma, Maen Roch, France),
125 anhydrous dicalcium phosphate “ACP” (Di-cafos A60, Chemische Fabrik Budenheim,
126 Budenheim, Germany), microcrystalline Cellulose “MCC” (Vivapur12, JRS Pharma,
127 Weissenborn, Germany) and starch (Lycatab C, Roquette, Lestrem, France). Magnesium
128 stearate (Partek Mg Lub, Merck, Darmstadt, Germany) was used for external lubrication
129 during tablet manufacturing. In addition, the apparent particle density of each powder was
130 determined using a helium pycnometer (AccuPyc 1330, Micromeritics, Norcross, GA,
131 USA). The measurements were performed in triplicate (10 purges and 10 runs). The
132 pycnometric density of each powder is presented in Table 1.

133 **3.2 Tablet manufacturing**

134 All tablets were manufactured on a compaction simulator Styl'One Evolution
135 (Medelpharm, Beynost, France). This device is a single station instrumented tableting
136 machine. It is equipped with force sensors (strain gauges) on both punches and on the
137 die wall, and the displacements of the punches are monitored using incremental sensors.
138 It is equipped with a separate engine for each punch. The compaction cycle was set to
139 simulate a Korsh XL 100 Euro-B at a rotation speed of 20 rpm. An example of the punch
140 displacement and axial force profiles of the simulated compaction cycle used to
141 manufacture MLac tablets at 200MPa is presented in the Figure S1 of the Supplementary
142 Material.

143 Tablets were made for each product presented above at two compression pressures (100
144 and 200 MPa) using Euro-B flat-faced punches with a diameter of 11.28 mm. Filling height
145 was modified in each case to obtain a final tablet thickness of 2 mm. In the case of MLac
146 and starch, supplementary tablets were manufactured. For MLac, tablets were also made
147 at 200 MPa with Euro-B flat faced punches of a diameter of 11.28 mm with a tablet
148 thickness of 1.5, 2.5 and 3 mm and with Euro-B flat faced punches of a diameter of 8 mm
149 and 16 mm with respectively a tablet thickness of 2 mm and 3 mm. Supplementary tablets
150 of starch were made at 200 MPa with Euro-B flat faced punches of a diameter of 10 mm
151 and a tablet thickness of 3 mm. Lubrication was made using an external system with a
152 pulsed air blow cabinet. The magnesium stearate powder was sprayed on the punches
153 and the die during 1200 ms. For each condition (pressure, product and size), 5 tablets
154 were manufactured to assess the test repeatability.

155 **3.3 Impulse excitation technique**

156 Damping ratios were measured based on the results of impulse excitations tests. Those
157 tests were made following the methodology presented earlier (Mazel and Tchoreloff,
158 2020; Meynard et al., 2021). As peak shapes and damping ratios are impacted by the
159 amount of energy given to the system to put it into motion, tablets were all dropped on a
160 hard surface (here, stainless steel) at a fixed height (1 cm height) to minimize the
161 variations of this energy during the experiments. In all the cases, to obtain a single
162 rebound, tablets were dropped on their lateral band. The sample free vibrations induced
163 by the impact were recorded using a microphone MM310 (Microtech Gefell GmbH, Gefell,
164 Germany). The data acquisition system was a DEWE-43 coupled with the software
165 Dewesoft X3 (Dewesoft, Trbovlje, Slovenia). Acquisition frequency was set to 200 kHz
166 and as a consequence the maximal detectable frequency was 78.1 kHz. More technical
167 details on the methodology are explained in (Mazel and Tchoreloff, 2020). Time-domain
168 amplitude signal was converted into a frequency-domain using a fast Fourier transform
169 (FFT) algorithm. A Blackman window with 2^{12} (= 4096) points was used. The frequency
170 resolution was 24.4 Hz. For each product and each condition, spectra were recorded on
171 5 tablets. On each tablet at least 40 spectra were acquired.

172 **3.4 Measurements using the half-power bandwidth method**

173 Modes with lower natural frequencies present higher amplitudes than those with higher
174 natural frequencies (an example can be seen in figure 1 of (Mazel and Tchoreloff, 2020)).
175 This is due to the fact that those higher modes are more difficult to excite since a lot of
176 energy is required to set the system to vibrate with those given mode shapes. Thus, in
177 order to compare tablet behaviours, we chose to evaluate the damping ratio ζ_A of the

178 mode A as presented in (Meynard et al., 2021) which corresponds to the first flexural
179 mode.

180 The variability of ζ_A due to the energy excitation was then quantified based on the study
181 of several frequency spectra for a given product. Due to the large quantity of data acquired
182 (at least 40 spectra per tablet), a Python sub-routine was developed in order to automatize
183 the evaluation of the modal damping ratio on each spectrum. To remove noised spectra
184 from the list of spectra studied, a manual check was then performed. Then, damping ratios
185 ζ_A were evaluated on the ten frequency spectra with the highest amplitudes of the peak
186 related to mode A. The value of ζ_A for a given product was then calculated as the mean
187 value of these ten measurements.

188

189 **4 Results and discussion**

190 **4.1 Characterization of tablet damping ratio**

191 Tablets with a diameter of $D = 11.28$ mm and a thickness of $h = 2$ mm were studied. As
192 presented elsewhere (Meynard et al., 2021), for this tablet dimension, the mode shape
193 related to mode A corresponds to the first natural frequency of the frequency spectra. The
194 damping ratio related to tablet mode A (ζ_A) was therefore characterized on tablets
195 manufactured with all the products studied and made at two different compaction
196 pressures (100 and 200 MPa) using the methodology presented previously. The results
197 are presented in Figure 2.

198 Note that all the damping ratios characterized were lower than 4 % ($\ll 1/(2\sqrt{2}) \approx 35\%$)
199 meaning that tablets in general are light damping systems. For each product relatively low

200 coefficients of variation were obtained (always under 0.18). This means that the
201 methodology developed makes it possible to obtain reproducible results. Moreover,
202 significant differences can be seen between the products. Indeed, for each compaction
203 pressure, the same tendency in ζ_A was observed: Starch > MCC > MLac and ACP. This
204 means that the methodology developed can differentiate the products based on their
205 damping behaviour. To the authors knowledge, it was the first time that the damping
206 behaviour of such materials was characterized.

207 Note that for a compaction pressure, the tendency observed in damping ratios was the
208 same as observed in viscoelasticity in (Desbois et al., 2020) where the viscoelasticity of
209 same type of products was characterized using an original in-die methodology of
210 characterization. The methodology proposed seems thus promising in terms of
211 viscoelasticity characterization. However, viscoelasticity is not the only phenomena which
212 can induce damping during the vibration of pharmaceutical tablets. Indeed, energy
213 dissipation can occur at the interfaces of the solid part of the material due to air/solid
214 interactions (frictions) in pores and along the external solid interface with air (Biot, 1956;
215 Takahashi and Tanaka, 2002). As tablets are porous solids, the impact of porosity on
216 damping must thus be verified. Another parameter that must be considered is
217 viscoplasticity as it can induce energy dissipation. Moreover, depending on the tablet
218 dimensions, some structural effects could also impact damping. Thus, in order to evaluate
219 adequately the relationship between tablet damping ratio ζ_A and viscoelasticity, the impact
220 of the other phenomena which can induce damping and which were described above (i.e.
221 viscoplasticity, porosity and tablet dimensions) were investigated.

222

223 **4.2 Effect of viscoplasticity**

224 During the impact resonance tests, tablets are solicited by impact. If the energy related to
225 this impact is high enough, tablet microstructures and properties could be modified, i.e.
226 plastic deformations could occur. If plastic deformation occurs, tablets can exhibit some
227 viscoplastic characteristics. It was thus important to verify the absence of plastic
228 deformations.

229 If plastic deformations occur during the test, this means that the properties of the tablet
230 should change including their elastic properties. As a consequence, the frequency of the
231 natural vibration should be impacted. As said in the material and method part, during the
232 test, the same tablet is dropped several times and each time the frequency spectrum is
233 recorded. If structural changes happen during the test due to plasticity, a shift in the natural
234 frequency should be obtained.

235 In order to evaluate this hypothesis, we chose to present here the results obtained on the
236 tablets made under 100 MPa, which are the weakest tablets and are thus more
237 susceptible to undergo plastic deformations. Evolution of the natural frequency of mode A
238 as a function of the frequency spectrum number (a spectrum with a number n was
239 measured after the n^{th} drop of the tablet) for each product are presented on Figure 3. The
240 10 spectra presented were those on which the damping ratios were measured.

241 No trend of evolution of the natural frequencies during the experiments was observed.
242 This was true for all the tests performed as also observed in (Mazel and Tchoreloff, 2020).
243 As the natural frequency is a material inherent property, the fact that this parameter
244 remained constant during the test series means that tablet microstructures and properties

245 remained the same. This confirms that the methodology used (i.e. drop of tablets from 1
246 cm height) was such that tablets were solicited in their elastic domain. We can therefore
247 consider negligible the plastic during the test. We can then neglect the influence of
248 viscoplasticity on the damping ratio ζ_A during the performed tests.

249

250 **4.3 Influence of porosity**

251 Tablet porosity was estimated using tablet density (evaluated with the measurements of
252 its dimensions and mass) and pycnometric density. Table 2 shows the tablet density as
253 well as their porosity for all the tablets manufactured with a diameter D of 11.28 mm and
254 a thickness h of 2 mm. As expected, for each product, an increase of compaction pressure
255 led to an increase of tablet density and thus a decrease of tablet porosity (Alderborn,
256 2001).

257 Two comments can be made comparing porosity and damping ratio results. Firstly, for a
258 given compaction pressure, the tendency in tablet porosity was: ACP > Starch > MCC >
259 MLac. However, we observed in Figure 2 a tendency in ζ_A different from the one observed
260 in tablet porosity (Starch > MCC > MLac and ACP). Thus, there is no direct relationship
261 between the tendency in ζ_A and tablet porosity.

262 Secondly, significant variations of porosity were observed from one pressure to another.
263 Nevertheless, on Figure 2, it can be seen that, for each product, the values of the damping
264 ratios at the two compaction pressures are not significantly different (overlapping of the
265 error bars). This means that a change in porosity has no significant influence on ζ_A . The
266 absence of impact of porosity on damping behaviour was already reported by several

267 authors using Dynamic mechanical analysis (Alberola et al., 1995; Radebaugh et al.,
268 1989; Van Der Voort Maarschalk et al., 1996). The influence of tablet porosity on ζ_A was
269 therefore neglected hereinafter.

270

271 **4.4 Impact of tablet dimensions**

272 During the process of tablet manufacturing, flat-faced tablets can be made with different
273 thicknesses or diameters. As the aim of the methodology proposed is to characterize the
274 viscoelasticity of the product, it is thus mandatory to verify that the result is not impacted
275 by structural effects, i.e. in our case by tablet dimensions (diameter and thickness). In
276 order to understand the influence of tablet dimensions on their damping ratio ζ_A , we
277 characterized MLac and starch tablets made at 200 MPa with different diameters and
278 thicknesses. Tablet dimensions were specified in section 3.2. As explained in (Meynard
279 et al., 2021) , the tablet dimensions have an influence on the natural frequencies.
280 However, the way tablet dimensions impact the natural frequency depends on the mode
281 shape studied. As a consequence, depending on tablet dimensions and due to frequency
282 shifts, it is possible that, in certain cases, the first frequency of the spectrum might not
283 correspond the mode A. Moreover, from a fundamental point of view, the damping factor
284 might not be exactly the same for the different modes (see section 2.1). It is thus important
285 to study always the same mode shape whatever the tablet dimensions. In our case, we
286 wanted to verify that, using the dimensions presented in section 3.2, the first frequency of
287 the spectrum always corresponded to the one related to mode A. Based on our previous
288 work, it was already known that the mode shape related to mode A corresponded to the
289 first natural frequencies for tablets with ($D = 11.28$ mm and $h = 2$ mm) and ($D = 11.28$

290 mm and $h = 2.5$ mm) (Meynard et al., 2021). In order to identify the mode shape related
291 to mode A for all tablet dimensions studied, we followed the same methodology as in
292 (Meynard et al., 2021) using an undamped modal analysis. The study was performed
293 using the finite element software Abaqus® 6.13 (Dassault Systèmes, Vélizy-Villacoublay,
294 France) with the Lanczos algorithm on 3-D free moderately thick cylindrical plates
295 (representing flat-faced cylindrical tablets) on a mesh of about 40000 nodes. More details
296 on the finite element calculations used can be found in (Meynard et al., 2021). It was
297 checked that the first mode observed always corresponded to the mode A for all the
298 tablets with the dimensions studied in this article.

299 The damping ratios ζ_A were then characterized for all the tablets studied, using in each
300 case, the first frequency peak of the spectrum . The influence of tablet dimensions on ζ_A
301 on MLac and starch tablets made at 200 MPa was presented in Figure 4.

302 Considering the error bars in Figure 4, no significant variations of the damping ratio ζ_A
303 were observed with respect to both tablet diameter and thickness for MLac and starch
304 tablets made at 200 MPa. Therefore, as seen for two products presenting very different
305 viscoelastic properties, it seemed that the effect of tablet dimensions on tablet damping
306 ratio ζ_A was negligible in the range of dimensions studied.

307

308 **4.5 Relationship between tablet damping ratio and viscoelasticity**

309 As explained above, energy loss in tablets leading to damping can be induced by tablet
310 viscoelasticity, viscoplasticity, porosity and dimensions. Negligible effects on tablet
311 damping ratio ζ_A were observed with respect of tablet viscoplasticity (section 4.2), tablet

312 porosity (4.3) as well as tablet dimensions (section 4.4) whereas the tendency observed
313 in damping ratios was the same as the one observed in viscoelasticity in (Desbois et al.,
314 2020) (section 4.1). Only the viscoelastic behaviour of tablets seemed to impact ζ_A .
315 Therefore, it can be conclude that the characterization of tablet damping ratio ζ_A makes it
316 possible to classify products based on tablet viscoelasticity. It can be noted that Desbois
317 and al. (Desbois et al., 2020), using a completely different methodology, found slight
318 changes in viscoelastic properties with porosity but without real trends. This was not found
319 in the present study. So, if it exists, the influence of porosity on the viscoelastic behaviour
320 is small and might not be detected by the present methodology.

321 Due to the simplicity of implementation of the half-power bandwidth method on frequency
322 spectra obtained using impact resonance, this indirect characterization of tablet
323 viscoelasticity is thus a time-saving method compared to the others methodologies of
324 relaxation tests or dynamic mechanical analysis proposed in the literature.

325

326 **5 Conclusions**

327 A methodology of characterization of tablet viscoelasticity based on impulse excitation
328 measurements was presented in this article. The relationship between tablet damping of
329 the first flexural mode and their viscoelasticity was investigated. Tablet damping ratio of
330 mode A was characterized using the half-power bandwidth method on frequency spectra
331 obtained by impulse excitation measurements.

332 The impact of other factors that might affect the damping ratio, like viscoplasticity, porosity
333 or tablet size, were found to be negligible. It was thus found that viscoelasticity was the

334 principal responsible of variations in the tablet damping ratio. This was confirmed by the
335 results found on tablets made from excipients with known viscoelastic behaviour.

336 In previous studies we already shown that impulse excitation technique could be used to
337 characterize the elastic behaviour of the tablet including its anisotropy (Mazel and
338 Tchoreloff, 2020; Meynard et al., 2021). The new results presented in the present work
339 make it possible to show that impact excitation is an easy-to-use and time-saving way to
340 characterize the global elastic/viscoelastic behaviour of pharmaceutical tablets. This
341 characterization can be of interest in order to understand the behaviour of formulations
342 during compaction. Impulse excitation technique is thus an interesting asset during the
343 development of pharmaceutical tablets.

344 **Legend to figures**

345 Figure 1: Illustration of the half-power bandwidth method

346 Figure 2: Damping ratios ζ_A for tablets ($D=11.28$ mm, $h=2$ mm, made with all the products
347 studied and made at 100 and 200 MPa)

348 Figure 3: Evolution of the natural frequency depending on the test performed for tablets
349 at 100 MPa (results related to one tablet for each product studied)

350 Figure 4: Impact of the tablet dimensions (diameter D and thickness h) on the damping
351 ratio ζ_A of tablets made at 200 MPa: a) MLac tablets and b) starch tablets

352 **Legend to tables**

353 Table 1: Pycnometric density of the studied powders

354 Table 2: Density and porosity of tablets manufactured with a diameter D of 11.28 mm and
355 a thickness h of 2 mm

356

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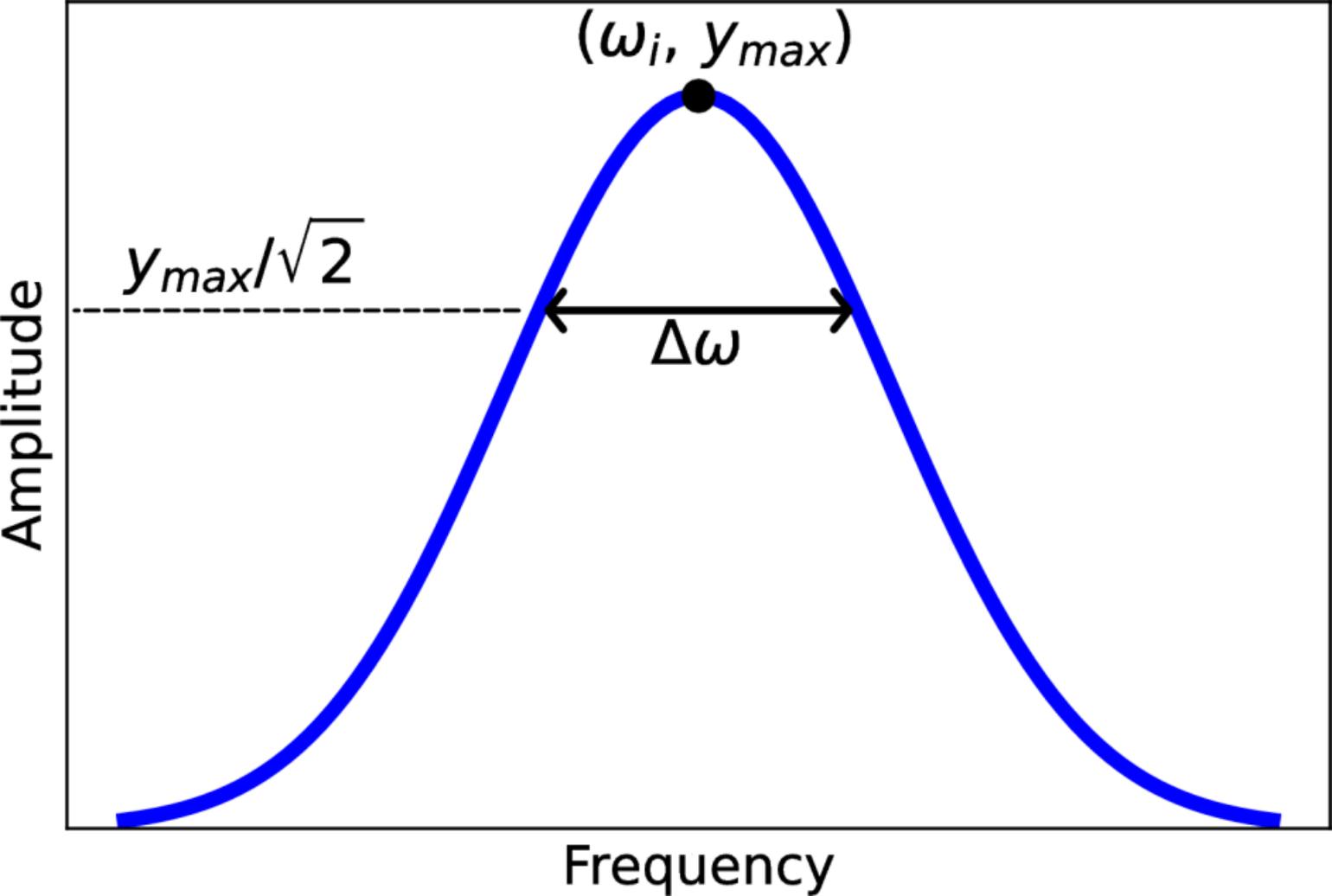
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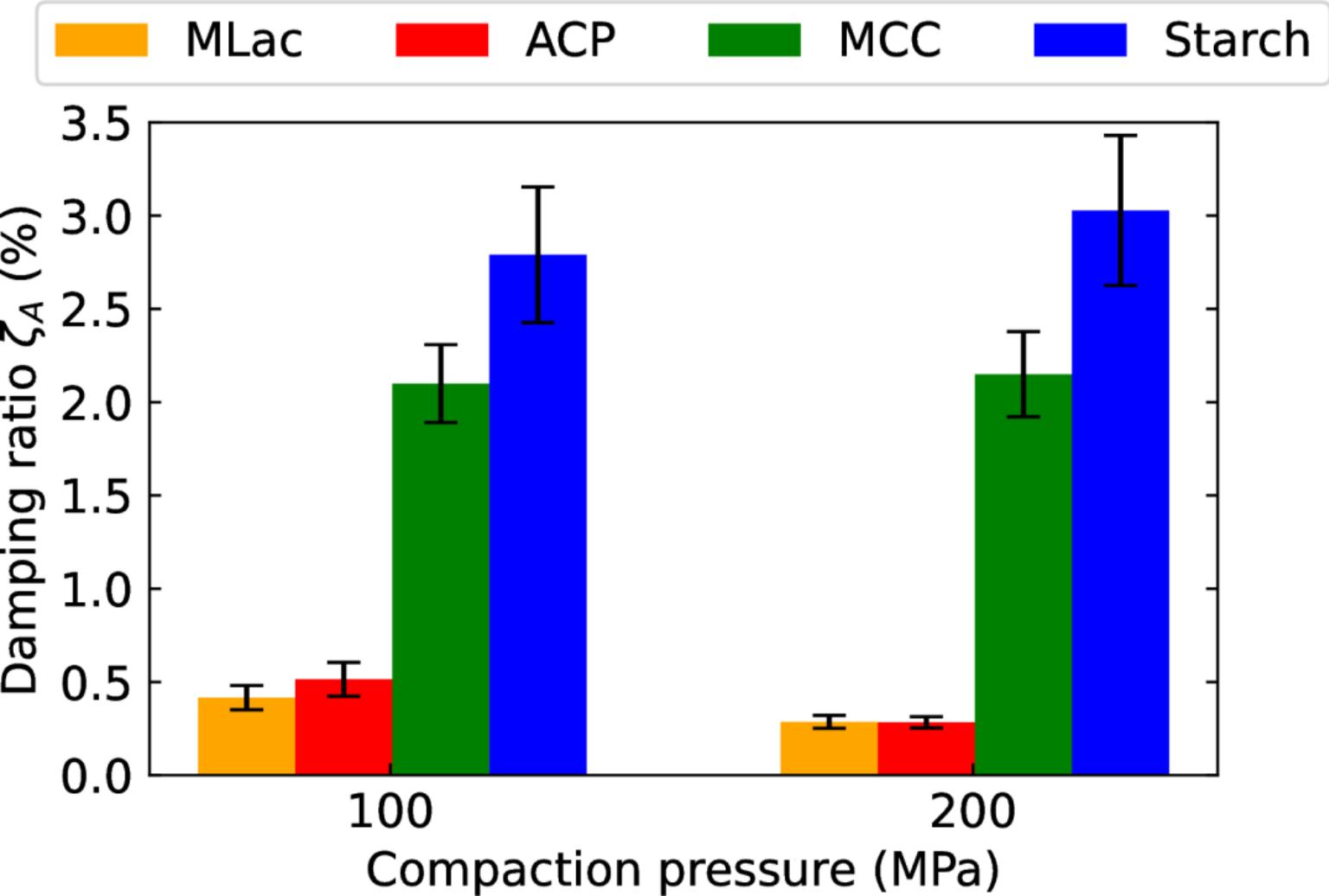
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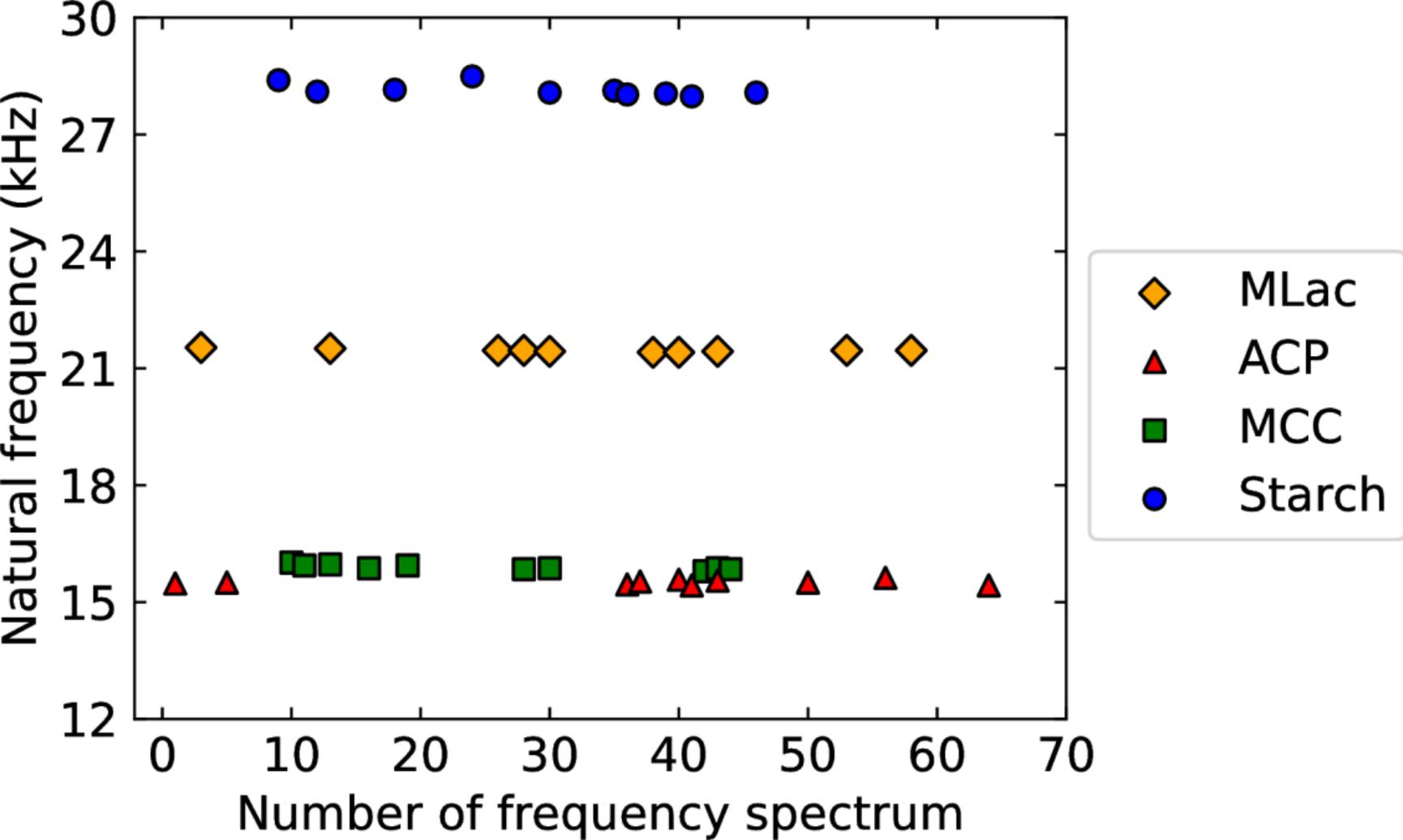
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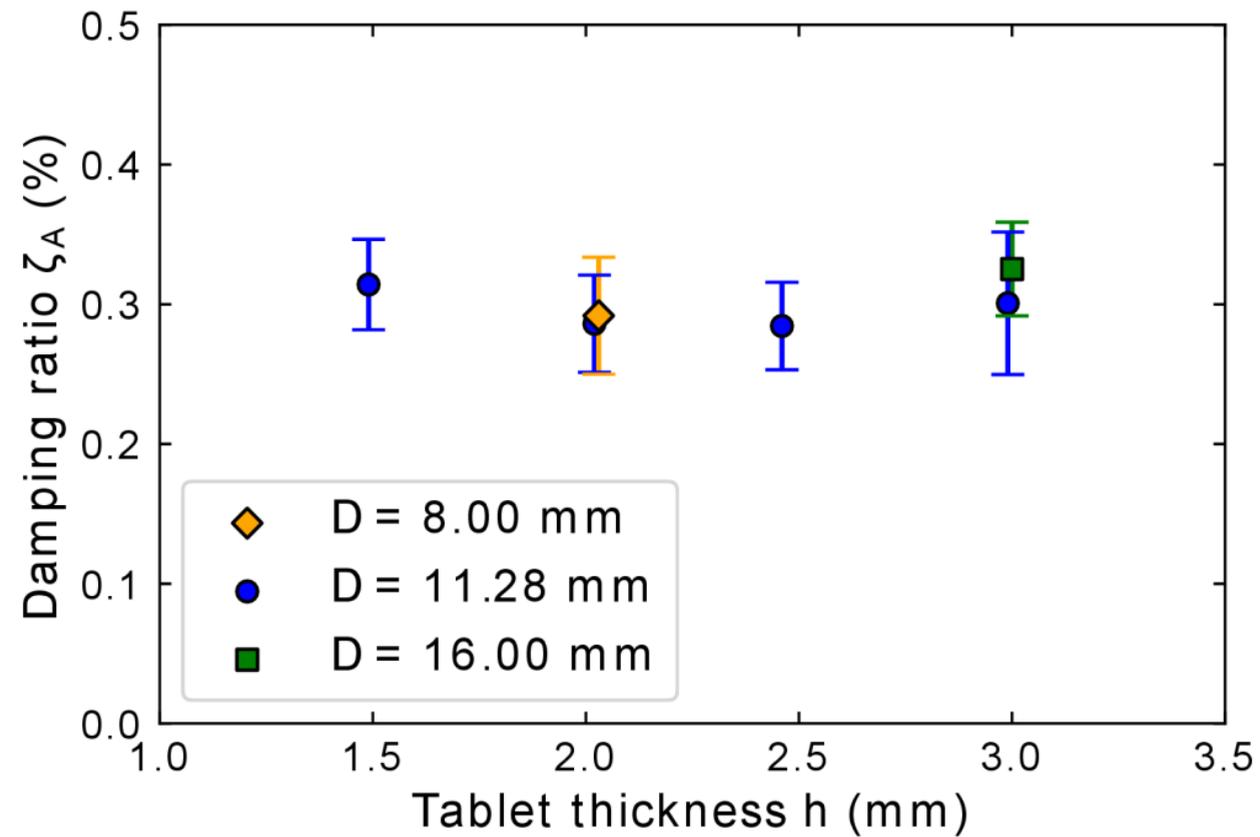
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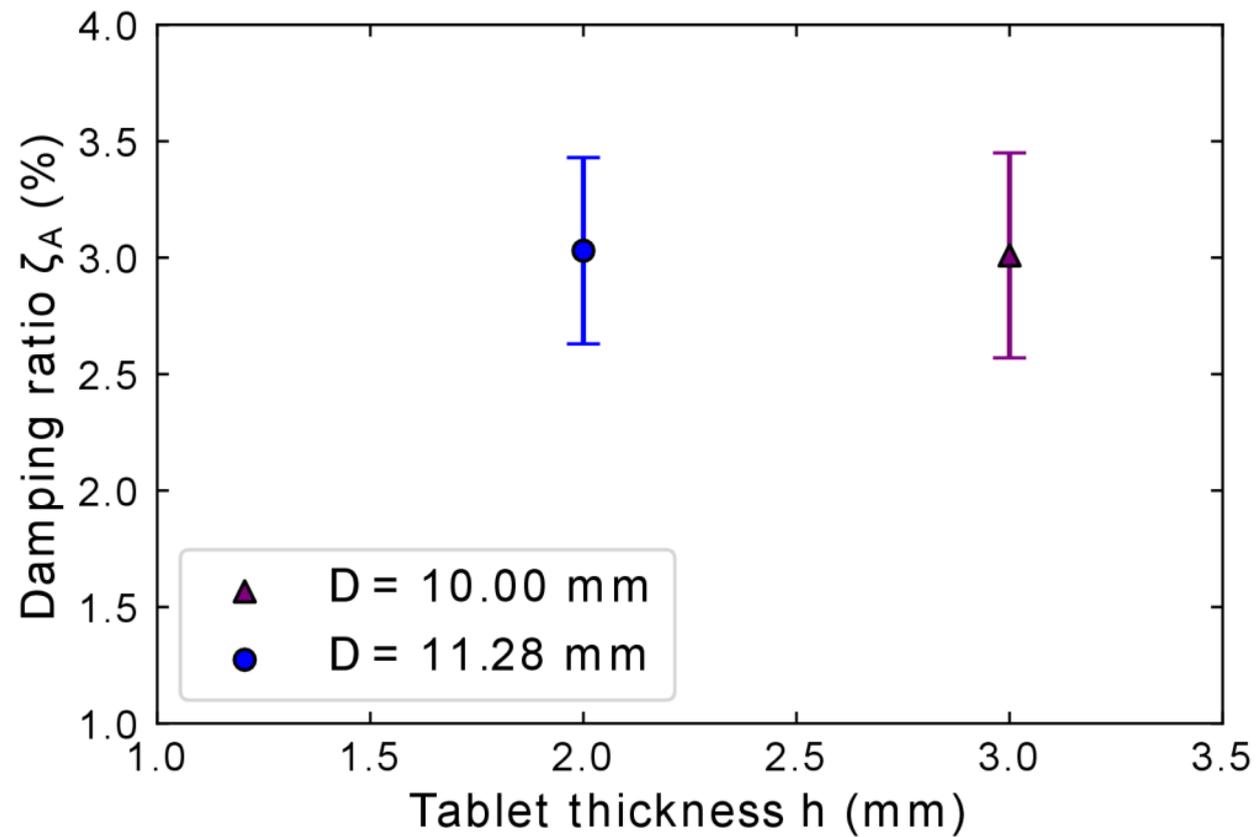








(a)



(b)

| Powder | True density (kg/m ³) |
|--------|-----------------------------------|
| MLac | 1533 ± 2 |
| ACP | 2853 ± 3 |
| MCC | 1609 ± 1 |
| Starch | 1495 ± 1 |

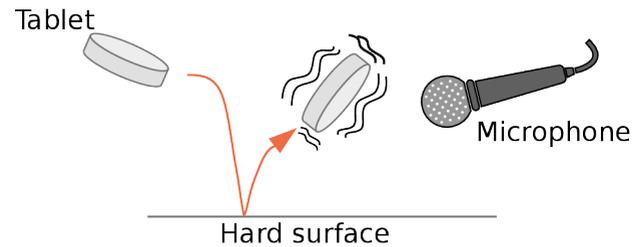
Table 1: Pycnometric density of the studied powders

| Product | Compaction pressure (MPa) | Tablet density (kg/m ³) | Tablet porosity (%) |
|---------|---------------------------|-------------------------------------|---------------------|
| MLac | 100 | 1268 ± 2 | 17.2 ± 0.1 |
| | 200 | 1362 ± 6 | 11.2 ± 0.1 |
| ACP | 100 | 1879 ± 5 | 34.2 ± 0.1 |
| | 200 | 2079 ± 11 | 27.2 ± 0.2 |
| MCC | 100 | 1300 ± 3 | 19.2 ± 0.1 |
| | 200 | 1424 ± 2 | 11.5 ± 0.1 |
| Starch | 100 | 1149 ± 1 | 23.2 ± 0.1 |
| | 200 | 1250 ± 1 | 16.4 ± 0.1 |

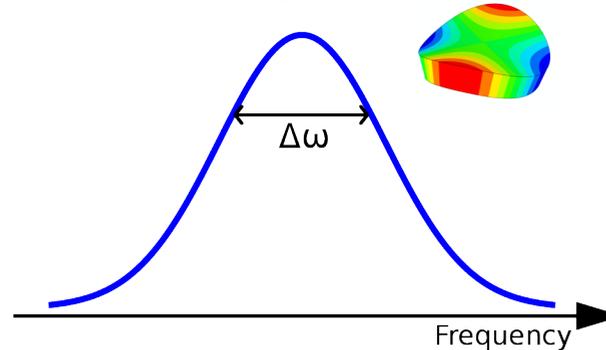
Table 2: Density and porosity of tablets manufactured with a diameter D of 11.28 mm and a thickness h of 2 mm

How to measure the viscoelasticity of cylindrical flat-faced tablets?

Impact resonance technique

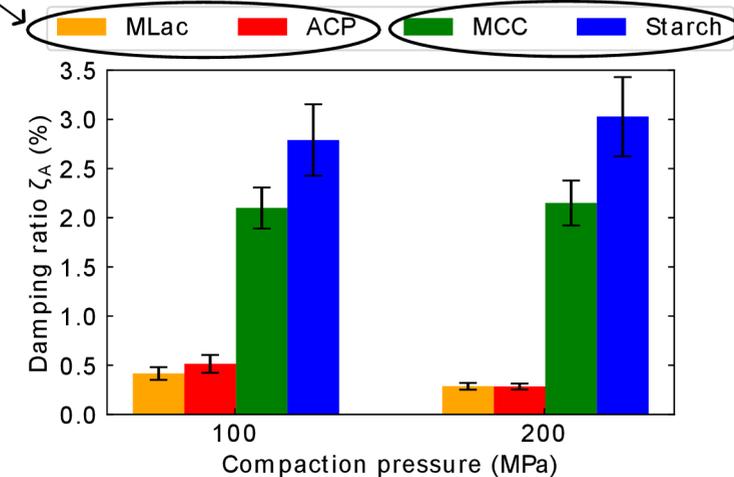


Damping behavior



Formulations with lower
viscoelastic behaviors
⇒ Lower damping

Formulations with higher
viscoelastic behaviors
⇒ Higher damping



Impact resonance makes it possible to estimate the damping of tablet first mode which is directly linked to tablet viscoelasticity.