



HAL
open science

Rheology of wheat flour dough at mixing

Guy Della Valle, Hubert Chiron, Luc Saulnier, Maude Dufour, Florence Hugon, Kamal Kansou

► **To cite this version:**

Guy Della Valle, Hubert Chiron, Luc Saulnier, Maude Dufour, Florence Hugon, et al.. Rheology of wheat flour dough at mixing. *Current Opinion in Food Science*, 2022, 47, pp.100873. 10.1016/j.cofs.2022.100873 . hal-03714931

HAL Id: hal-03714931

<https://hal.inrae.fr/hal-03714931>

Submitted on 22 Jul 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Rheology of wheat flour dough at mixing**

2

3 Guy Della Valle^{1*}, Maude Dufour^{1,2}, Florence Hugon², Hubert Chiron¹, Luc Saulnier¹, Kamal Kansou¹

4 ¹INRAE UR-1268 Biopolymères Interactions et Assemblages, 44316 Nantes, France

5 ²La Boulangere & Co, 85140 Essarts en Bocage, France

6

7 * corresponding author: guy.della-valle@inrae.fr

8

9 **Abstract**

10 The baking industry performs common technological (empirical) tests. Unfortunately, the results
11 hardly predict the dough behaviour on-line. This paper first reviews the most common methods to
12 assess the rheological properties of the dough, including empirical tests, small and large
13 deformations methods. A second section describes the relations between rheological properties and
14 dough behaviour at the critical step of dough mixing. We put forward a tentative interpretation of
15 these relations based on dough structural changes supported by results from imaging or
16 spectroscopic methods. Finally, a review of simple models consistent with the physical understanding
17 of the dough behaviour is presented as tools that scientist and engineers can use to interpret
18 experimental data, perform system analysis and anticipate the product properties.

19

20

21

22 **Introduction**

23 Anticipating the mechanical behaviour of the wheat flour dough is a major issue for the baking
24 industry. With the increasing variability of the wheat quality, due to environmental changes or to
25 sourcing diversification, it becomes essential to comprehensively assess the common rheological
26 models in a review with a view to examine their capacity to support decision in industry.

27 Interestingly, most rheological properties of the dough are determined as soon as the mixing
28 operation, the first operation of the processes. The mixing brings the mechanical energy and the
29 deformation required to distribute and hydrate homogeneously the flour constituents and to form the
30 network of gluten proteins. The gluten network is largely responsible for the visco-elastic properties
31 of the dough, its role in the retention and the stabilization of the air cells in the dough is well
32 documented [1,2]. A non-negligible amount of air (air fraction or porosity ≥ 0.1) is actually trapped
33 during mixing [1], which conditions the fermentation and eventually many quality criteria of bakery
34 products. This includes nutritional properties as well, such as Glycaemic Index and dietary fiber
35 content [2, 3], also strongly dependent of the dough rheology at mixing.

36 The present review offers a concise overview of the advances in dough rheology techniques and
37 models and propose guidelines for improving suitability to issues of the baking industry.

38

39 **Dough rheological properties**

40 Many rheological tests can be performed on dough. They can be classified according to the strain
41 mode implemented (shear or extension), the variable imposed (strain or stress) and its variation with
42 time (dynamic or oscillatory, or steady).

43

44 **Empirical testing**

45 Due to the essential role of rheological properties in the evaluation of the technological quality of a
46 flour, and therefore of its commercial value, manufacturers have developed empirical measurement
47 methods, to mimic processing conditions [4]. The Farinograph[®] measures the torque developed
48 during kneading in order to draw a consistency curve which presents a peak indicating the optimum
49 development of the dough; the Extensograph[®] measures the force required to stretch a dough
50 cylinder down its middle to determine its resistance; the Rheofermentometer[®] follows the gas
51 release of a dough under stress, and thus predicts its ability to expand during fermentation; the
52 Alveograph[®] measures the pressure required to break a film of dough, the area under the recorded
53 pressure curve would be related to the "force" of the flour. Clearly, this test is among the most

54 popular among professionals, and still receives scientific attention, e.g. for determining the
55 technological value of the wheat varieties [5]. Although these methods may be reproducible when
56 conveniently handled, their results, generally expressed in arbitrary units, can only be used to
57 perform relative comparison of a set of flours and the test conditions are generally insufficient to
58 support a physical interpretation based on the flour composition or the dough structure. Indeed,
59 they involve different modes of deformation simultaneously in an uncontrolled way, which prevents
60 the relevant determination of intrinsic rheological properties in relation to the dough structure.

61 **Small deformations (“fundamental rheology”)**

62 Dynamic shear measurements are carried out at low strains ($\leq 0.1\%$ for wheat flour doughs), i.e. in
63 the linear viscoelastic domain (LVD). In practice, they require a few grams of dough prepared in small
64 laboratory kneaders, such as the Mixograph[®], where the continuous torque measurement can detect
65 peak formation, which reflects the optimum consistency of the dough [6]. These testing conditions
66 are far from those encountered in the process, and do not generally lead to good correlations
67 between the results, i.e. dough viscoelastic properties, with flour processing performances [7].
68 Nevertheless, they have shown that the dough behaves more like a solid than a liquid ($G' > G''$), and
69 highlighted the role of high molecular weight glutenins (HMWG) and their entanglements in the
70 creation of the gluten network [8], whilst dough viscoelastic behavior could be represented by a
71 weak gel power law model, the exponent of which reflects the network connectivity [9]. At higher
72 strain, beyond LVD, large amplitude oscillatory shear tests applied to gluten gels, combined with this
73 mathematical model, show that network connectivity decreases and evidence segments extensibility
74 [10]. However, starch/gluten blends fail to reproduce the viscoelastic behavior of flour doughs [11,
75 12], which indirectly highlights the role of minor constituents, such as the polysaccharides from cell
76 wall components (CWC).

77 In the linear domain as well, the dynamic thermo-mechanical analysis (DMA), simulates the behavior
78 of dough in compression or in tension during baking, by following variations of the storage module E'
79 with temperature. The storage modulus $E'(T)$ curve displays a minimum value (E'_{min}) around $T=50$
80 °C and a maximum value (E'_{max}) close to $T=75$ °C. The larger the ratio (E'_{max} / E'_{min}), the more the
81 gluten network crosslinking of the dough and, to a lesser extent, the starch granules swelling,
82 between 50 and 75°C [13, 14].

83 **Large deformations**

84 Measurements performed in large deformations can be associated to the behavior of the dough
85 during processing. The shear viscosity $\eta(\dot{\gamma})$ can be measured by capillary rheometry, provided that

86 the pressure fluctuations, linked to the slippage and dough structure sensitivity, are controlled and
87 reduced [15, 16]. In rotational rheometry, the application of creep tests (with grooved plates), by
88 imposing various stresses, allows determining a flow curve $\eta(\dot{\gamma})$ [12, 17, 18], that can be fitted by
89 the Cross model:

$$\eta = \eta_0 / (1 + (\dot{\gamma} / \dot{\gamma}_0)^n) \quad (1)$$

90 where η_0 is the plateau (Newtonian) viscosity; at higher shear rate, viscosity decreases according to
91 a power law with a slope - n; the transition between the two regimes may be identified by the value
92 of $\dot{\gamma}_0$ (s^{-1}), the reverse of which can be considered as a relaxation time of the dough, of one hour as
93 an order of magnitude.

94 Extension is involved in many food processes and it induces a deformation that implies the
95 deformation of the structural entities (molecules, aggregates, droplets, etc) along the streamlines
96 [19]. The ring stretch test, popularized as Kieffer test, provides a measurement of the uniaxial
97 elongational viscosity [20], while the Extensional Viscosity Fixture is used to characterize the dough
98 strain-hardening behaviour with a better control of strain [21]. The bi-extensional, or biaxial
99 elongation, viscosity, η_e , is the property by which the dough resists the growth of gas cells during
100 fermentation, highlighting its strain-hardening behavior, and reflecting its capacity for gas retention
101 and stability of the dough at rest [22]. η_e can be determined by a uniaxial compression of the dough
102 between lubricated plates (Lubricated Squeezing Flow, LSF) [23, 24]. In the case of dough made from
103 cereal flours, the measurements of the stress σ , of the equi-biaxial strain ϵ_e , and of the strain rate $\dot{\epsilon}_e$,
104 lead to the determination of η_e according to the following equation [25, 26]:

$$\sigma = \eta_e * \dot{\epsilon}_e = K (\dot{\epsilon}_e)^m * \exp(SHI * \epsilon_e) \quad (2)$$

105 where K and m are the consistency and flow indices, respectively, defined at constant strain value,
106 SHI being the shear hardening index (> 1). Note that the consistency index K should not be
107 confounded with the consistency derived from torque curves recorded on instrumented mixers
108 (Farinograph, Mixograph, etc). Although dough behaves like a solid rather than a fluid, it never
109 reaches a true state of equilibrium. However, the comparison of the results of LSF tests carried out at
110 constant displacement speed with those obtained at constant strain rate [27], shows that, at
111 constant strain, η_e can be expressed by a power law as deduced from equation (2). Bi-extensional
112 properties can also be determined by the bubble inflation test [28]. The results of this test can be
113 related to those of the Chopin Alveograph [29, 30], provided the accurate measurement of the dough
114 film thickness [31], and $\epsilon_e \leq 1.5$, which actually holds for the proofing stage [32]. The same group has
115 determined the shear and extension behaviours, inc. the use of LSF, and proposed a composite

116 micromechanical model that evidenced the decohesion between gluten network and starch grains
117 [33]. Note that mathematical expressions of stress, modulus or viscosity, as function of strain, and
118 strain rate, which are simply illustrated by eq.1-2, are mathematical rheological models, also called
119 constitutive equations (see Figure 1). More accurate mathematical models may be found in the
120 literature, especially to take into account small and large strains, shear and elongational
121 deformations, and time dependence. Finally, rheological tests are mostly performed on unyeasted
122 dough, although fermentation and metabolites have been shown to reduce slightly extensibility and
123 extensional viscosity [34, 35], which was attributed to gluten network degradation [36].

124

125 **Dough mixing follow-up**

126 Various mixer geometries and working conditions affect bread dough readiness, delineated by
127 adequate mixing time and level of water added [37]. Dough readiness is usually assessed by an
128 optimum consistency target at mixing with the Farinograph, which is a sound and practical indicator
129 for the baker. However, it remains difficult to relate this property with rheological properties,
130 although some indicators, such as maximum values of SHI or of extensional stress, are inferred for
131 the optimum dough development [38, 39]. The way the different devices impart strain to the dough
132 samples induces distinct mechanical treatments which likely clouds the relations between the results
133 [40].

134 The dough development along mixing is followed by the measurement of the power (or torque)
135 curve $P(t)$, and of the Specific Mechanical Energy (SME) deduced from the area under the curve
136 (Figure 2). For wheat, values of SME for an optimum dough development generally stand in the
137 interval [20-60 kJ.kg⁻¹] [39, 41]. The negative correlation between the SME and storage ratio
138 measured by DMA shows that SME contributes to the creation of the gluten network [41]. This
139 relation is further specified through the decoupling of the mechanical and kinetic effects on the
140 unextractable fraction of glutenin polymers [42]. The optimum SME value depends on the type of
141 deformation mode which results from the mixer geometry. Indeed, with a z-blade and planetary
142 mixers, shear and extensional deformations contribute in a distinct manner to the development of
143 dough structure [41, 43]. By analogy with fluid mixing principles [42, 44], whatever the mixer
144 geometry, the shear viscosity η can be evaluated through power measurements:

$$145 \quad \text{SME} / (t_m * \rho_d) = \eta * (A_m \cdot \dot{\gamma})^2 \quad (3)$$

146 t_m being the mixing time and ρ_d the density of the dough ($\approx 1.2 \text{ kg.L}^{-1}$ [3]), A_m is a constant,
147 characteristic of the mixer geometry linking $\dot{\gamma}$ to the rotation speed of the mixer arm. The flow curve

148 of a dough can thus be used to determine A_m (= 1.55 for a z-mixer with a capacity of 5 kg) [41]). A_m
149 values can be used to compare the performance of different mixers, in particular their capacity to
150 dissipate (shear) or store (elongation) energy in the dough, the latter being more favorable to dough
151 structuring, whereas the former leads to premature degradation of the gluten network [45, 46]. In
152 addition, the spreading of the $P(t)$ curve was found to be influenced by dough extensibility [47].

153 Besides its use for rheometry, $P(t)$ can monitor dough changes, for instance when incorporating
154 ingredients to the flour such as insoluble wheat components (CWC) to increase the dietary fiber
155 content, a huge challenge in baking industry. When CWC are added, SME increases, and so does the
156 dough consistency index (K in Eq. (2)), while the ratio (E'_{max} / E'_{min}) measured by DMA decreases
157 [48]. The increase of the dough consistency index K is unlikely to be the result of a higher gluten
158 network structuring since CWC can inhibit the creation of S-S bonds directly involved in this process
159 [49]. Most likely, the increase of viscosity and SME due to CWC addition are due to the higher solid
160 volume fraction F_v , by analogy with the viscous behavior of a suspension. However, the dependence
161 of K as a function of F_v cannot be satisfactorily described by a usual rheological model of suspension,
162 possibly because of various effects of CWC addition [50].

163 Finally, the role of mixing is also to entrap air, in order to promote expansion and cellular structure
164 creation during fermentation, a purpose for which pressure changes provides another degree of
165 freedom, whilst the rheological properties of degassed dough may be assumed constant [51].

166

167 **Structural changes during mixing (& methodology)**

168 Rheological properties reflect the dough structure, and rheological models are more reliable and
169 efficient when they are based on structural features. Describing this link is an important research
170 topic for the domain. At the microscopic level, dough can be considered as a composite material,
171 composed roughly of starch grains and aggregated proteins (the gluten network), also containing
172 dietary fibers originating from the starchy endosperm (e.g pentosans in wheat white flour) and
173 possibly from the outer part of the grain (bran) in the case of whole grain flours), mixed with other
174 ingredients (water, fat, sugar, etc.) (Figure 3). Many works have determined the modifications of
175 protein network during mixing through biochemical analyses (see for instance [42, 43, 52]), whilst
176 imaging techniques and non-destructive methods, have been much less employed, although
177 complementary. Ultra sound is a good example of an efficient in-line method that can evaluate
178 dough rheological properties and explore air bubbles size distribution, provided deconvolution
179 between water distribution and gluten network development has been performed [53].

180 Vibrational spectroscopic techniques have provided valuable insights on dough protein
181 secondary structure [54]. The NIR spectra modifications recorded during mixing have been linked to
182 physical and chemical mechanisms taking place inside the dough [55], whereas amide bands
183 identified by MIR spectroscopy suggested that dough development was linked to the ratio β -sheets /
184 random coil [56]. Conformational changes studied by FT-Raman spectroscopy enabled to put forward
185 that the decrease of dough extensibility due to fiber addition can be attributed to the increase of β -
186 sheets [57]. By applying fluorescence spectroscopy completed with chemometrics, the dough mixing
187 phases (hydration, dough development, and stability and softening) were clearly separated and
188 different wheat flours could be identified on the basis of their bread baking performance [58].

189 Although partly destructive, the environmental scanning electronic microscopy (ESEM) has
190 shown that dough mixing led to starch granules embedded in a protein matrix of gluten strands (also
191 see Figure 3), coinciding with lower $\tan \delta$ value ($=G''/G'$) [59]. At a larger scale, confocal scanning
192 laser microscopy (CSLM) with appropriate staining, evidenced different gluten/starch morphologies
193 according to SME reflecting different mixing and deformation mode. The heterogeneity in the form
194 of gluten aggregates appearing at larger SME reflected dough overmixing [43]. CSLM images can be
195 analysed by protein network analysis (PNA), thus, lacunarity (i.e. amount and size of network gaps)
196 was found to be related to the shear viscoelastic modulus G^* for dough obtained by mixing with
197 gluten modifying agents [60, 61].

198 Whatever dough morphology, water distribution among components is an important factor
199 for dough rheological properties. It continuously evolves during mixing and cannot be simply inferred
200 from the water holding capacity of individual component [62]. Low Resolution Proton Nuclear
201 Magnetic Resonance (LR 1H NMR) – and most specifically the Carr-Purcell-Meiboom Gill (CPMG)
202 pulse sequence – has been used to investigate the relationship between biopolymer interactions and
203 water dynamics responsible for the evolution of the rheological properties of dough, flour model
204 systems and bread, since the 1970s [63]. In dough, different proton populations were observed and
205 tentatively assigned to water more or less linked with main flour constituents, i.e. starch and gluten
206 [64]. The evolution of the proton populations has been studied during mixing [65], storage [66, 67],
207 when changing flour/dough composition [68, 69] or according to dough hydration level [70, 71, 65].
208 It was interpreted as chemical/physical transformations of the flour constituents. For example, the
209 increase of dough hydration level impacts only the most mobile fraction of protons, which
210 corresponds to the free water outside starch granule [64]. Both the amount of protons and their
211 mobility increased with water [71, 65], reflecting a lower rigidity of the dough, as observed by a
212 decrease of modulus G measured by DMA [70]. These recent works can describe the changes of

213 distribution of water in dough and open prospects for a better understanding of the changes of
214 dough rheological properties at mixing.

215 So integrating the complementary information brought by these different methods should be
216 an important research perspective to provide rheological measurements and models with sound
217 structural basis.

218

219 **Modelling dough at mixing**

220 Modelling can help to provide insights on the mechanisms involved in dough changes, spare
221 machine time devoted to experimental trials, simulate process conditions in order to predict their
222 impact on dough and bread properties, allow an accurate control to maintain optimal quality. In the
223 field of materials manufacturing, the use of numerical software is now common practice from the
224 design to the process and logistics control, and part of the Industry 4.0 approach. Likely because of
225 the lack of knowledge about physical properties of foods and the underlying mechanisms of
226 structural changes, it is less common in food processing, although numerical modelling has been
227 developed in food processing specially by applying Computational Fluid Dynamics [72]. This
228 approach, also called deterministic, or mechanistic, mostly relies on the theoretical frame of
229 Continuum Mechanics. It is complex and, besides strong investment, needs to be fueled by a
230 rheological model (Figure 1). In a complementary manner, experimental approaches may be guided
231 by statistical models which require the fitting of experimental data according to numerical procedure
232 and rationale. This approach can lead to the optimization of a product or a process in shorter time;
233 such models are data-driven models [73]. Both approaches – deterministic and data driven, have in
234 common to represent, in various mathematical forms, the relations between input and output
235 variables.

236 **Data-based models**

237 These models have in common to rely on the data directly obtained from experiments on the process
238 itself. They include classical approaches in food science and technology, and more recent ones that
239 have gained considerable interest since the developments of machine learning (artificial intelligence)
240 [74]. Many works have used experimental design and response surface models, for instance to
241 determine the mixing conditions (time, power) that lead to an optimized cellular structure after
242 fermentation [75]. Likewise, baking results were predicted from farinograph measurements using
243 stepwise linear regression and artificial neuronal networks [76]. Artificial neural networks were also
244 used to predict the power delivered to the dough and its temperature for various mixing conditions

245 [77]. The analysis of power consumption, deduced from torque measurement, or Farinograph
246 consistency, or profiles $P(t)$, provides a simple mean to test various factors such as mixer filling,
247 dough moisture [78], and determine extension properties for different wheat varieties [79]. The
248 redistribution (migration) of water between starch, gluten and fibers in model bread dough has been
249 determined from the changes of dough consistency during mixing [68]. Despite good predictive
250 power, the model validity is generally limited by the dataset used to “learn” the parameters, i.e. the
251 experimental domain. Integrating the physical understanding of the dough behaviour in the models
252 is a way to improve robustness by limiting aberrant prediction out of the domain of validity.

253

254 In this view, between data-driven and deterministic models, the concept of basic knowledge model
255 (BKM) has been proposed as a practical medium to transfer and implement food science knowledge
256 beyond the laboratory [80, 81]. Rheological models (e.g. Eq. 1,2) can be considered as BKM, because
257 they are easy to handle and they capture essential knowledge about material behaviour. Actually, no
258 deterministic model, based on continuum mechanics, can describe all physical mechanisms involved
259 during dough mixing, whereas, at industry level, the design of baked products is still relying on
260 experts ‘ know-how. Knowledge-based models have been proposed to integrate this expertise with
261 scientific understanding of the dough rheology, in order to predict quality criteria from flour
262 characteristics and process conditions [82, 83].

263

264 **Deterministic (Mechanical) models**

265 Dough mixing is a complex operation because the material is non-Newtonian, viscoelastic and
266 evolutive, hence it has a complex constitutive equation; moreover, the geometry is complicated with
267 a free surface, since the dough surface continuously changes because of the motions of the mixing
268 arm and bowl. Therefore, analytical mechanical models of planetary mixers, based on dimensional
269 analysis and applied to Newtonian fluids, only predict mixer’s performances [84] whereas the
270 solution of momentum equations require numerical methods like FEM (Finite Element Modelling),
271 implemented by Computational Fluid Dynamics (CFD). Therefore, dough mixing has first been
272 modelled using a Newtonian model for viscosity in order to determine the stream lines and shear
273 rate fields [85], whereas various non-Newtonian models have been tested in a 2D geometry mixer
274 [86]. Both complexities, geometry and rheological behavior, have been taken into account recently,
275 leading to a satisfactory description of dough flow patterns [87]. In this study, the rheological
276 behaviour was described by the joined use of two models, namely White-Metzner, that involves a
277 single relaxation time, and Bird-Carreau, which is essentially similar to eq. (1). Further, using CFD,
278 the flow of dough, behaving as a power law fluid, in tube and contraction geometries was simulated

279 to identify the strain domains that cause damage and unstable process regions [88]. Such simulations
280 can be useful not only to optimize mixer geometries and processes conditions but also to capture
281 structural changes of dough. The selection of the rheological model for simulations studies results
282 from a trade-off between the accuracy of the prediction and the costs of computation, but recent
283 progresses in computational resources suggest that more comprehensive rheological models can be
284 integrated in a near future.

285
286

287 **Conclusions**

288 This review shows that in spite of the many studies dedicated to dough rheology and mixing, the
289 structure of dough microstructure has not been related to its rheological properties yet, and in turn,
290 to its behaviour during processing. Modelling this operation, either by deterministic or data driven
291 approaches is certainly a determinant support with that regard. Maybe in a near future, “smart”
292 mixers will stop automatically the mixing in anticipation of an exaggerated drop of the dough
293 viscosity, or in case of obvious underhydration, resulting from an error of a water dosage. Besides
294 process control, the sourcing of raw material, and especially wheat flour, could be improved by
295 specifying further dough processing criteria, thanks to a better knowledge of its rheology. Recent
296 advances in spectroscopic methods, especially NMR, open perspectives to improve these aspects.
297 Actually, climate change leads to an evolution of the wheat production worldwide while the demand
298 for healthier and safer food changes the classical view of product quality. These transitions impose a
299 better control of wheat quality, of the process, and, more generally, a better knowledge of the
300 rheological properties of food materials.

301

302 **Declaration of interest:**

303 Nothing declared

304 **List of figures**

305 Figure 1: Conceptual view of the relationships between dough structure, rheological properties and
306 mixing process. Continuous arrows mean “influences” whereas dotted ones mean “gives information
307 about”. Rheological model is also called “constitutive equation”. Please note that rheology under
308 small deformations, i.e. fundamental, can also lead to constitutive models but not applicable to
309 modelling process, because of too different strain conditions.

310

311 Figure 2: Examples of time-power (P) curves recorded during dough mixing (m=3kg) for different
312 rotation speeds of the spiral (O: 320 rpm, ●: 200 rpm, ●: 80 rpm) and energy (dotted line at bottom)
313 for 200rpm, adapted from [44].

314

315 Figure 3: Different levels of matter organisation of wheat flour dough during mixing: from left to
316 right: straight from the mixer, CSLM image (width 500 μm) of composite morphology (starch: green,
317 protein: red) with air bubbles, SEM image (width 50 μm) of starch granule entrapped in gluten
318 filaments, arrangement of gluten β -sheets in water environment (from [89]), and protein
319 interactions (dotted and cont.: H₂ and S-S bonds, resp.) from [90]. Images from INRAE.

320

321

322

323 **References and recommended reading**

324 Papers of particular interest, published within the period of review, have been highlighted as:

325 ● of special interest

326 ●● of outstanding interest

-
1. Bellido GG, Scanlon MG, Page JH, Hallgrímsson B: **The bubble size distribution in wheat flour dough.** *Food Res Int* 2006, **39** :1058–1066.
 2. Poutanen K, Sozer N, Della Valle G: **How can technology help to deliver more of grain in cereal foods for a healthier diet ?** *J Cereal Sci* 2014, **59** : 327-336,.
 3. Saulnier L, Micard V, Della Valle G : **Structure du pain et index glycémique.** *Cahiers de nutrition et diététique* 2014, **49** : 61-66,
 4. Hajselova M, Alldrick AJ: **Analysing wheat and flour.** In *Bread making. Improving quality* Edited by Cauvain SP, Woodhead Publish Ltd, Cambridge (UK), 2003, pp 187-198.
 5. Schou Jodal AS, Lambertsen Larsen K. **Investigation of the relationships between the alveograph parameters.** *Sci Reports*, 2021, **11**: 5349.
 6. Gras PW, Carpenter HC, Anderssen RS: **Modelling the developmental rheology of wheat flour dough using extension tests.** *J Cereal Sci* 2000, **31**: 1-13.
 7. Stojceska V, Butler F: **Investigation of reported correlation coefficients between rheological properties of the wheat bread doughs and baking performance of the corresponding wheat flours.** *Trends Food Sci Technol* 2012, **24**: 13-18.
 8. Dobraszczyk BJ, **The physics of baking: rheological and polymer molecular structure–function relationships in breadmaking.** *J non Newtonian Fluid Mech* 2004, **124**: 61-69.
 9. Gabriele D, de Cindio B, D'Antona P: **A weak gel model for foods.** *Rheol Acta* 2001, **40**, 154 -161.
 10. Ng TSK, McKinley GH, Ewoldt RH: **Large amplitude oscillatory shear flow of gluten dough: A model power-law gel.** *J Rheol* 2011, **55**, 627 -654.
 11. Uthayakumaran S, Newberry M, Phan-Thien N, Tanner, R: **Small and large strain rheology of wheat gluten.** *Rheol Acta* 2002, **41**, 162-172.
 12. Lefebvre J: **An outline of the non-linear viscoelastic behaviour of wheat flour dough in shear.** *Rheol Acta* 2006, **45**: 525-538.
 13. Angioloni A, Dalla Rossa M: **Dough thermo-mechanical properties: influence of sodium chloride, mixing time and equipment.** *J Cereal Sci* 2005, **41** : 327-331.
 14. Rouillé J, Chiron H, Colonna P, Della Valle G, Lourdin D : **Dough/crumb transition during French bread baking.** *J Cereal Sci* 2010, **52**: 161-169.
 15. Breuillet E, Yildiz E, Cuq B, Kokini J: **Study of the anomalous capillary Bagley factor behavior of three types of wheat flour doughs at two moisture contents.** *J Text studies* 2002, **33**: 315-340.
 16. Hicks CI, See H: **The rheological characterisation of bread dough using capillary rheometry.** *Rheol Acta* 2010, **49**:719–732
 17. Rouillé J, Della Valle G, Lefebvre J, Sliwinski E, vanVliet T: **Shear and extensional properties of bread doughs affected by their minor components.** *J Cereal Sci* 2005, **42**: 31-43.
 18. Bonnand-Ducasse M, Della Valle G, Lefebvre J, Saulnier L: **Effect of wheat dietary fibres on bread dough development and rheological properties.** *J Cereal Sci* 2010, **52**, 200-206.

-
19. Rodriguez-Gonzalez F, Bello-Perez LA: **Extensional properties of macromolecules.** *Current Opinion in Food Science* 2016, **9**:98–103.
 20. Tschoegl NW, Rinde JA, Smith TL: **Rheological properties of wheat flour doughs, I. Method for determining the large deformation and rupture properties in simple tension.** *J. Sci. Food Agric.* 1970, **21**: 65-70.
 21. Meerts M, Cervera AR, Struyt R, Cardinaels R, Courtin CM, Moldenaers P. **The Interplay Between the Main Flour Constituents in the Rheological Behaviour of Wheat Flour Dough,** *Food Bioprocess Technol* 2017, **10**:249–265.
 22. van Vliet T, Janssen AM, Bloksma AH, Walstra P: **Strain hardening of dough as a requirement for gas retention.** *J. Texture Studies* 1992, **23** : 439-460.
 23. Chatraei SH, Macosko CW, Winter HH: **Lubricated squeezing flow: a new biaxial extensional rheometer.** *J Rheol* 1981, **25** 433-443.
 24. van Vliet T: **Strain hardening as an indicator of bread-making performance: A review with discussion.** *J Cereal Sci* 2008, **48**: 1-9.
 25. Launay B, Michon C: **Biaxial extension of wheat flour doughs: lubricated squeezing flows and stress relaxation properties.** *J Texture Studies* 2008, **39**: 496-529
 26. Turbin-Orger A, Shehzad A, Chaunier L, Chiron H, Della Valle G: **Elongational properties and proofing behaviour of wheat flour dough.** *J Food Eng* 2016, **168**, 129-136.
 27. Kouassi-Koffi JD, Launay B, Davidou S, Kouame LP, Michon C: **Lubricated squeezing flow of thin slabs of wheat flour dough: comparison of results at constant plate speed and constant extension rates.** *Rheol Acta* 2010, **49**: 275-283.
 28. Dobraszczyk BJ, Roberts CA: **Strain hardening and dough gas cell-wall failure in biaxial extension.** *J Cereal Sci* 1994, **20**: 265-274
 29. Charalambides MN, Wanigasooriya L, Williams JG, Chakrabarti S: **Biaxial deformation of dough using the bubble inflation technique. I. Experimental.** *Rheol. Acta* 2002, **41**: 532-540.
 30. Charalambides MN, Wanigasooriya L, Williams JG : **Biaxial deformation of dough using the bubble inflation technique. II. Numerical modelling.** *Rheol. Acta* 2002, **41** : 541-548.
 31. Charalambides MN, Wanigasooriya L, Williams JG, Goh SM, Chakrabarti S: **Large deformation extensional rheology of bread dough.** *Rheol Acta* 2006, **46**: 239–248.
 32. Turbin-Orger A, Babin P, Boller E, Chaunier L, Chiron H, Della Valle G, Dendievel R., Réguerre AL, Salvo L : **Growth and setting of gas bubbles in a viscoelastic matrix imaged by X-ray microtomography: the evolution of cellular structure in fermenting wheat flour dough.** *Soft Matter* 2015, **11**, 3373-3384.
 33. Mohammed MAP, Tarleton MN, Charalambides MN, Williams JG: **Mechanical characterization and micromechanical modeling of bread dough.** *J Rheol* 2013, **57**, 249-272.
 34. Connelly RK, McIntier RL: **Rheological properties of yeasted and nonyeasted wheat doughs developed under different mixing conditions.** *J Sci Food Agric* 2008, **88**, 2309-2323.
 35. Meerts M, Cardinaels R, Oosterlinck F, Courtin CM, Moldenaers P: **The effects of yeast metabolites on the rheological behaviour of the dough matrix in fermented wheat flour dough.** *J Cereal Sci* 2018, **82**, 183-189.
 - Comprehensive study that evidences the impact of metabolites after addition to unfermented dough, thanks to the combination of different rheological techniques at small and large deformations, in shear and extension.
 36. Alpers T, Tauscher V, Steglich T, Becker T, Jekle M: **The Self-Enforcing Starch–Gluten System—Strain–Dependent Effects of Yeast Metabolites on the Polymeric Matrix.** *Polymers* 2021, **13**, 30-39.
 37. Parenti O, Guerrini L, Mompin SB, Toldrà M, Zanoni B : **The determination of bread dough readiness during kneading of wheat flour: a review of the available methods.** *J Food Eng* 2022, In Press
<https://doi.org/10.1016/j.jfoodeng.2021.110692>

-
- Useful and thorough review about the different methods to control dough mixing, especially optimal consistency for various equipments. Processing variables during mixing (e.g. torque) are related to structural aspects of dough, inc. gluten network, through various analytical methods.
 - 38. Meerts M, Cardinaels R, Oosterlinck F, Courtin CM, Moldenaers P: **The Impact of Water Content and Mixing Time on the Linear and Non-Linear Rheology of Wheat Flour Dough.** *Food Biophysics* 2017, **12**: 151–163.
 - 39. Peighambardoust SH, van der Goot AJ, Boom RM, Hammer RJ: **Mixing behaviour of a zero-developed dough compared to a flour-water mixture.** *J Cereal Sci* 2006, **44**, 12-20
 - 40. Tietze S, Jekle M, Becker T: **Possibilities to derive empirical dough characteristics from fundamental rheology.** *Trends Food Sci Technol* 2016, **57**,1-10
 - 41. Shehzad A, Chiron H, Della Valle G, Lamrini B, Lourdin D: **Rheological and energetical approaches of wheat flour dough mixing.** *J Food Eng* 2012, **110**: 60-70.
 - 42. Baudouin F, Nogueira TL, van der Mijnsbrugge A, Frederix S, Redl A, Morel MH. **Mechanical activation of gluten network development during dough mixing.** *J Food Eng* 2020, **283**: 110035.
 - ● Valuable application of mixer as a rheometer that relates process to structure, leading to a power correlation of viscosity with gluten aggregation ratio. Authors show that the power relation exhibits same exponent as for gluten aggregation ratio relation with plateau modulus formerly determined using oscillatory rheometry.
 - 43. Peighambardoust SH, van der Goot AJ, van Vliet T, Hamer RJ, Boom RM: **Microstructure formation and rheological behaviour of dough under simple shear flow.** *J Cereal Sci* 2006, **43**: 183–197
 - 44. Delaplace G, Guerin R, Leuliet JC, Chhabra RP: **An analytical model for the prediction of power consumption for shear-thinning fluids with helical ribbon and helical screw ribbon impellers.** *Chem Eng Sci* 2006, **61**: 3250 – 3259.
 - 45. Peighambardoust SH, van der Goot AJ, Hammer RJ, Boom RM: **Effect of simple shear on the physical properties of glutenin macro polymer (GMP).** *J Cereal Sci* 2005, **42**: 59–68.
 - 46. Peressini D, Peighambardoust SH, Hamer RJ, Sensidoni A, van der Goot AJ: **Effect of shear rate on microstructure and rheological properties of sheared wheat doughs.** *J Cereal Sci* 2008, **48**: 426-438.
 - 47. Dufour M, Hugon F, Chiron H, Della Valle G, Kansou K, Saulnier L : **Characterization of the bread dough behavior during kneading by modeling the power curve.** *55th Congres of French Rheology Group 2021*, Bordeaux, 26-28 Oct.
 - 48. Le Bleis F, Chaunier L, Chiron H, Della Valle G, Saulnier L: **Processing wheat flour dough and French bread enriched with wheat bran.** *J Cereal Sci* 2015, **65**: 167-174.
 - 49. Noort MWJ, van Haaster D, Hemery Y, Schols HA, Hamer RJ: **The effect of particle size of wheat bran fractions on bread quality e evidence for fibre protein interactions.** *J Cereal Sci* 2010, **52** : 59-64.
 - 50. Della Valle G, Chiron H, Le-Bail A, Saulnier L : **Food structure development in cereal and snack products.** In *Handbook on food structure development* Edited by Styropoulos FP, Lazidis A & Norton IT, RSC, Cambridge, UK, 2019, pp 151-172.
 - 51. Trinh L, Lowe T, Campbell GM, Withers PJ, Martin PJ: **Bread dough aeration dynamics during pressure step-change mixing: Studies by X-raytomography, dough density and population balance modelling.** *Chem Eng Sci* 2013, **101**: 470-477.
 - 52. Ooms N, Delcour J: **How to impact gluten protein network formation during wheat flour dough making.** *Current Opinion in Food Science* 2019, **25**: 88–97.
 - 53. Koksel F, Scanlon MG, Page JG: **Ultrasound as a tool to study bubbles in dough and dough mechanical properties: A review.** *Food Res Int* 2016, **89**: 74–89.
 - Comprehensive review of the use of ultrasound to control dough rheological properties with clear background about a technique that allows online application.
 - 54. Sadat A, Corradini MG, Joye IJ: **Molecular spectroscopy to assess protein structures within cereal systems.** *Current Opinion in Food Science* 2019, **25**:42–51.

-
55. Ait Kaddour A, Barron C, Morel MH, Cuq B: **Dynamic Monitoring of Dough Mixing Using Near-Infrared Spectroscopy: Physical and Chemical Outcomes.** *Cereal Chem* 2007, **84**: 70–79.
56. Ait Kaddour A, Mondet M, Cuq B: **Application of two-dimensional cross-correlation spectroscopy to analyse infrared (MIR and NIR) spectra recorded during bread dough mixing.** *J Cereal Sci* 2008, **48** : 678–685.
57. Nawrocka A, Miś A, Szymańska-Chargot M: **Characteristics of Relationships Between Structure of Gluten Proteins and Dough Rheology – Influence of Dietary Fibres Studied by FT-Raman Spectroscopy.** *Food Biophys* 2016, **11**: 81–90.
58. Haseeb AM, Nache M, Waffenschmidt S, Hitzman B: **Characterization of farinographic kneading process for different types of wheat flours using fluorescence spectroscopy and chemometrics.** *Food Control* 2016, **66**: 44-52.
59. Letang C, Piau M, Verdier C: **Characterization of wheat flour-water dough. Part I: rheometry and microstructure.** *J Food Eng* 1999, **41**: 121-132.
60. Bernklau I, Lucas L, Jekle M, Becker T: **Protein Network Analysis – A new approach for quantifying dough microstructure.** *Food Res Int* 2016, **89**: 812–819.
61. I. Lucas I, Petermeier H, Becker T, Jekle M: **Definition of network types – Prediction of dough mechanical behaviour under shear by glutenmicrostructure.** *Sci Reports* 2019, **9**: 4700.
- This paper, which comes after a series of papers from the same group on this topic, reports a complete description of gluten network arrangement obtained by quantitative imaging using CSLM and strives to relate these features to rheological properties in shear, at low and large deformations.
62. Bushuk W : **Distribution of Water in Dough and Bread.** *Baker's Digest* 1996, **40** : 38-41.
63. Leung HK, Magnuson JA, Bruinsma BL : **Pulsed Nuclear Magnetic Resonance study of water mobility in flour doughs.** *J Food Sci* 1979, **44**: 1408-1411.
64. Bosmans GM, Lagrain B, Deleu LJ, Fierens E, Hills BP, Delcour JA : **Assignments of proton populations in dough and bread using NMR relaxometry of starch, gluten, and flour model systems.** *J Agric Food Chem* 2012, **60**: 5461-70.
65. Parenti O, Guerrini L, Zanoni B, Marchini M, Tuccio MG, Carini E. **Use of the 1H NMR technique to describe the kneading step of wholewheat dough: The effect of kneading time and total water content.** *Food Chem* 2021, **338**: 128120.
- This paper carefully discusses the links between the behavior of whole wheat flour dough and the level of water binding with the flour constituents.
66. Curti E, Bubici S, Carini E, Baroni S and Vittadini E : **Water molecular dynamics during bread staling by Nuclear Magnetic Resonance.** *Food Sci Technol* 2011, **44** : 854-859.
67. Bosmans GM, Lagrain B, Ooms N, Fierens E and Delcour JA : **Biopolymer Interactions, Water Dynamics, and Bread Crumb Firming.** *J Agric Food Chem* 2013, **61**: 4646-4654.
68. Miś A., Krekora M, Niewiadomski Z, Dziki D, Nawrocka A : **Water redistribution between model bread dough components during mixing.** *J Cereal Sci* (2020), **95** : 103035
- This article proposes a solid modelling study to relate dough properties at mixing (consistency) to the distribution of water in three components, gluten, starch and fibers. The model has potential to analyse the effect of the hydration mechanisms and water transfer between components and asses its impacts on gluten network.
69. Leys S, De Bondt Y, Bosmans G, Courtin CM: **Assessing the impact of xylanase activity on the water distribution in wheat dough: A 1H NMR study.** *Food Chem* 2020, **325**: 126828.
- Another careful application of NMR technique to assess the distribution of water between components of dough model system. Authors evidence the role of xylanase to reduce the water retention capacity of insoluble arabinoxylans.
70. Assifaoui A, Champion D, Chiotelli E and Verel A. **Rheological behaviour of biscuit dough in relation to water mobility.** *Int J Food Sci Technol* 2006, **41** : 124 - 128.
71. Doona C, Baik MY : **Molecular mobility in model dough systems studied by time-domain nuclear magnetic resonance spectroscopy.** *J Cereal Sci* 2007, **45** : 257-262.

-
72. Datta AK: **Toward computer-aided food engineering: Mechanistic frameworks for evolution of product, quality and safety during processing.** *J Food Eng* 2016, **176**: 9-27
73. Sablani SS, Rahman MS, Datta AK, Mujumdar AS: *Handbook of Food and Bioprocess Modeling Techniques*. CRC Press, Boca Raton, US, 2007.
74. Zhou L, Pan S, Wang J, Vasilakos AV: **Machine learning on big data: Opportunities and challenges.** *Neurocomputing* 2017, **237** : 350-361.
75. Kansou K , Chiron H, Della Valle G, Ndiaye A, Roussel P, Shehzad A : **Modelling wheat flour dough proofing behaviour: effects of mixing conditions on porosity and stability.** *Food Bioprocess Technol* 2013, **6**: 2150-2164
76. Hermannseder B, Haseeb AM, Kugler P, Hitzmann B: **Prediction of baking results from farinograph measurements by using stepwise linear regression and artificial neuronal networks.** *J Cereal Sci* 2017, **76**: 64-68
77. B. Lamrini B, Della Valle G, Trelea IC, Perrot N, Trystram G: **A New Method for Dynamic Modelling of Bread Dough Kneading Based on Artificial Neural Network.** *Food Control* 2012, **26**: 512-524.
78. Hwang CH, Gunasekaran S: **Determining Wheat Dough Mixing Characteristics from Power Consumption Profile of a Conventional Mixer.** *Cereal Chem* 2001, **78**: 88–92.
79. Verbyla AP, Saint-Pierre C, Peterson CJ, Ross AS, Appels R: **Fourier modelling, analysis and interpretation of high-resolution mixograph data.** *J Cereal Sci* 2007, **46**: 11–21.
80. Della Valle G, Chiron H, Cicerelli L, Kansou K, Katina K, Ndiaye A, Whitworth M, Poutanen K: **Basic knowledge models for the design of bread texture.** *Trends Food Sci Technol* 2014, **36**: 5-14.
81. Kansou K, Laurier W, Charalambides MN, Della Valle G, Djekic I, Hailu Feyissa A, Marra F, Thomopoulos R, Bredeweg B : **Food modelling strategies and approaches for knowledge transfer.** *Trends Food Sci Technol* 2022, **120**: 363-373
82. Ndiaye A, Della Valle G, Roussel P : **Qualitative modelling of a multi-step process: the case of French breadmaking.** *Expert Syst Appli* 2009, **39** : 1020-1038.
83. Kansou K, Chiron H, Della Valle G, Ndiaye A, Roussel P: Predicting the quality of wheat flour dough after mixing by modelling expert’s know-how. *Food Res Int* 2014, **64**: 772-782.
84. Auger F, Delaplace G, Bouvier L, Redl A, André C, Morel MH: **Hydrodynamics of a planetary mixer used for dough process: Influence of impeller speeds ratio on the power dissipated for Newtonian fluids.** *J Food Eng* 2013, **118**: 350–357.
85. Binding DM, Couch MA, Sujata KS, Webster MF: **Experimental and numerical simulation of dough mixing in filled geometries.** *J Food Eng* 2003, **58**: 111-123.
86. Connelly RK, Kokini JL: **The effect of shear thinning and differential viscoelasticity on mixing in a model 2D mixer as determined using FEM with particle tracking.** *J non Newtonian Fluid Mech* 2004, **123**: 1-17.
87. Abu-Farah L, Goudoulas TB, Hooshyar S, Germann N: **Numerical and experimental investigation of dough kneading in a three-dimensional spiral kneader.** *Phys Fluids* 2019, **31**: 113104.
- This article well illustrates the various aspects of numerical modelling of wheat flour dough mixing, constitutive & momentum equations, (spiral) mixer geometry, and presents impressive simulated images of dough surface compared with experimental ones.
88. C. I. Hicks CI, See H, Fletcher DF, Ekwebelam C: **The shear rheology of bread dough: Analysis of local flow behaviour using CFD.** *Food Bioprocess Processing* 2012, **90**: 361–369.
89. Kim YR, Cornillon P, Campanella OH, Stroschine RL, Lee S, Shim JY: **Small and large deformation rheology for hard wheat flour dough as influenced by mixing and resting.** *J Food Sci* 2001, **73**: E1-E8
90. Kontogiorgos V: **Microstructure of hydrated gluten network.** *Food Res Int* 2011, **44**: 2582–2586

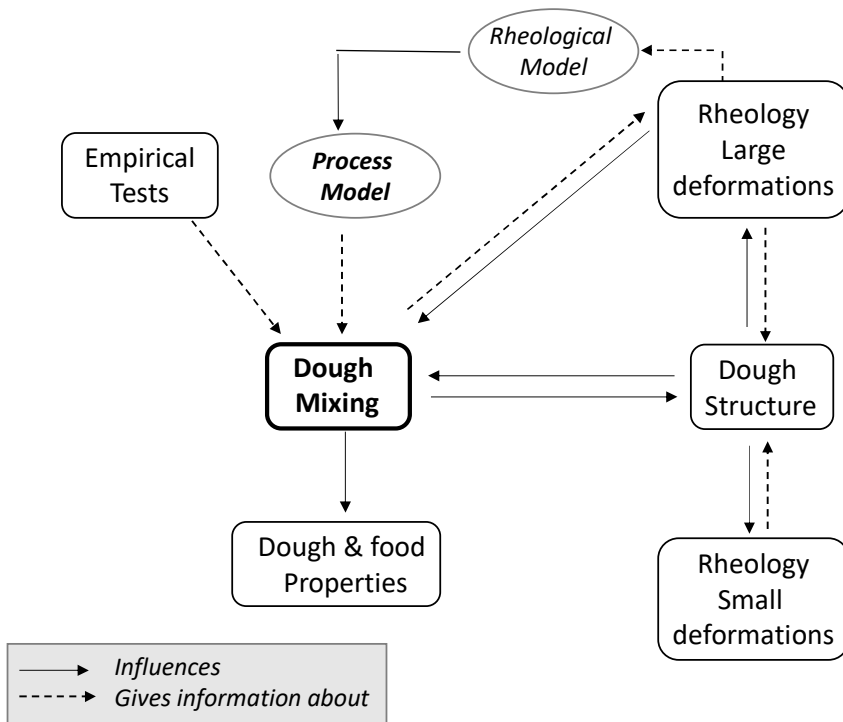


Fig.1

Dough Rheology Mixing

Della Valle et al.

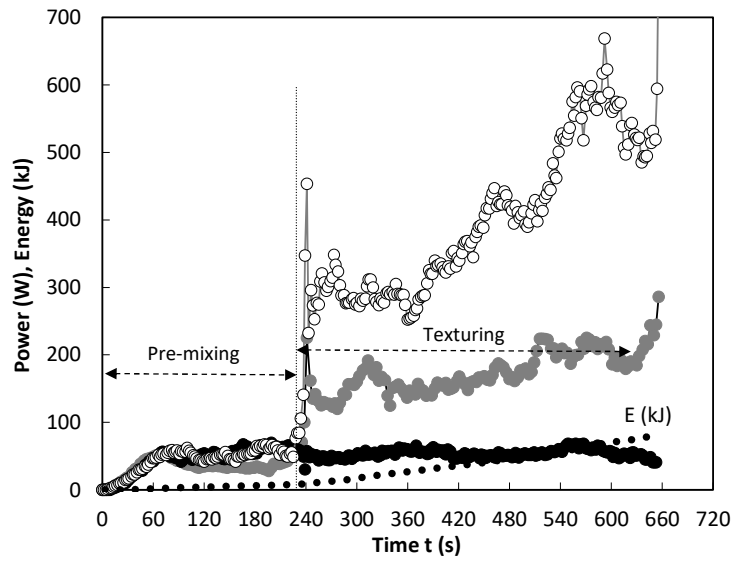


Fig.2

Dough Rheology Mixing

Della Valle et al.

