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STUDY OF DIC HYDROTHERMAL TREATMENT EFFECT ON RHEOLOGICAL
PROPERTIES OF STANDARD MAIZE (SMS), WAXY MAIZE (WMS), WHEAT (WTS)
AND POTATO (PTS) STARCHES

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1 **1. Abstract**

2 Standard maize (SMS), waxy maize (WMS), wheat (WTS) and potato (PTS) starches were
3 hydrothermally treated by Instantaneous Controlled Pressure Drop (DIC) process at different
4 pressure levels (1, 2 and 3 bar) corresponding to the temperatures of 100, 122 and 136°C,
5 respectively. The rheological properties and particle size of treated starches under various
6 conditions were compared to the native ones. The results showed for all starches, except for
7 WTS, a reduction of the consistency coefficient and the yield stress (τ_0) with increased
8 intensity of the hydrothermal treatment conditions. Furthermore, τ_0 vanished for severe
9 treatment conditions. The DIC treatment yielded an increased fluidity and a loss of the
10 conservative modulus of the pastes, as a result of partial gelatinization of starch granules. The
11 extent of the observed effect depended on the botanical origin. Wheat starch exhibited a
12 different behaviour: the consistency coefficient and the conservative modulus being higher for
13 DIC treated starch except for the most severe conditions.

14 2. Introduction

15 Starch has many applications in food and non-food industries. As an ingredient, it is extracted
16 from only a few species such as maize, wheat, potato, rice, tapioca, and sago. Pregelatinized
17 starches have been widely used for many foods as a major ingredient to provide thickened
18 textures at temperatures below the gelatinization temperature. They are obtained from native or
19 modified starch, by drum drying (Vallous et al., 2002) or by extrusion cooking (Barron et al.,
20 2000). Other processes of physical modification have been explored to improve qualities of the
21 starch such as annealing (Tester et al., 2000; Jayakody and Hoover, 2008) and heat moisture
22 treatment (HMT) (Kulp and Lorenz, 1981; Hoover and Manuel, 1996; Jacobs, et al., 1998;
23 Collado and Corke, 1999; Tester et al., 2000; Gunaratne and Hoover, 2002; Vermeylen et al.,
24 2006; Tukomane et al., 2007; Gunaratne and Corke, 2007, Chung et al., 2009). These two latter
25 treatments differ in the water content, temperature and processing time used. Annealing occurs
26 under large excess of water (50 to 60%) and relatively low temperatures (below the
27 gelatinization temperature), while the HMT is conducted under restricted moisture content (10-
28 30%) and higher temperatures (90-120 °C). Both treatments are applied over large periods of
29 time (10-16h). The main effects of HMT are loss of birefringence, increased gelatinization
30 temperature, broadened or unchanged gelatinization temperature range, change in X-ray
31 diffraction patterns, reduced swelling volume and solubility, with consequent changes in
32 functionality (Donovan et al., 1983; Collado and Corke, 1999; Gunaratne and Hoover, 2002).
33 Annealing results in improved perfection of the crystallites within starch granules that narrows
34 the gelatinization temperature interval; consequently, gelatinization temperatures shifted
35 towards higher values (Hublin, 1994; Jacobs et al., 1998; Tester et al., 2000). The enthalpy of
36 gelatinization remains unchanged or is moderately increased depending upon annealing
37 conditions (moisture content and time) and the botanic origin (Karlsson and Eliasson, 2003;
38 Lawal, 2005; Jayakody and Hoover, 2008) in contrast to HMT. The semi-crystalline structure

39 of starch granules is modified by these two usual physical treatments without disrupting the
40 integrity of granule (Lim et al., 2001).

41 HMT starches have generally been performed at the laboratory scale and many authors have
42 reported that such conditions produce inhomogeneous samples with lumps of gelatinized starch
43 beside heat-moisture treated starch. For this reason, pressure is often required to ensure
44 sufficient heating. To obtain a uniform heat distribution and rapid penetration of steam into the
45 starch granules, Maruta et al. (1994) improved the conventional method by creating a reduced
46 pressure in the vessel before the injection of live steam. This method was designated by these
47 authors as the reduced-pressurized heat moisture treatment (RP-HMT).

48 The DIC treatment (Instantaneous Controlled Pressure Drop) has been developed at the
49 laboratory as well as the pilot scale (Rezzoug et al., 2000), for drying and texturizing of food
50 products such as pasta products (Maache-Rezzoug and Allaf, 2005). As for the RP-HMT
51 process, an initial vacuum is applied before the treatment which is performed under high
52 temperature/high steam pressure; the hydro-treatment step is then followed by an abrupt
53 pressure drop towards vacuum pressure contrary to the RP-HMT treatment. This step induces a
54 rapid modification of the thermodynamic equilibrium reached during the pressurisation (P_1, T_1)
55 towards another equilibrium state (P_2, T_2). This new state induces a rapid cooling and the
56 resulting temperature value depends on the vacuum pressure level (Zarguilli et al., 2009). The
57 originality of the DIC process compared to other hydrothermal treatments is that starch is
58 treated **at an initial** moisture content of 12.5% (wet basis), no hydration step being then used.
59 During the treatment, the heating of starch is obtained by the absorption of latent heat of steam
60 condensation which causes an increase in the moisture content as the processing time and
61 pressure level increase (Zarguili et al., 2009).

62 The major effects observed after DIC treatment are almost similar to HMT treatment except
63 that the gelatinization temperature range is narrowed as observed with annealing (Hublin, 1994;

64 Jayakody and Hoover, 2008). This result suggests that the treatment firstly induced the melting
65 of crystallites of low cohesion (low stability) which required less energy to melt. Consequently,
66 the residual structure after the DIC treatment contained crystallites with a greater stability
67 (cohesion) (Maache-Rezzoug et al., 2008). Preliminary studies on standard and waxy maize
68 starches (Loisel et al., 2006, Zarguili et al., 2006) showed that the thermal properties of DIC
69 treated starch depend on the processing time and the steam pressure level. Increasing these two
70 parameters induces an increase in the onset (T_{onset}) and in the peak (T_{peak}) temperatures of
71 gelatinization and a reduction in gelatinization enthalpy. The occurrence of a partial or total
72 gelatinization was clearly attested by the decrease of enthalpy and a loss of birefringence under
73 polarized light. The X-ray diffraction pattern confirmed the partial or total loss of the
74 crystalline structure of native starch depending on the conditions of the DIC treatment: the
75 relative crystallinity of hydrothermally treated maize starch decreased and the polymorphic
76 type changed. The A-type crystalline pattern was progressively lost with the increase of
77 processing pressure (≥ 2 bar), and was substituted by the V_h -type X-ray diffraction pattern,
78 corresponding to the formation of amylose-lipid complexes. At severe DIC conditions (pressure
79 level of 3 bar), the typical peaks of A-type X-ray diffraction pattern were substituted
80 completely by the ones of the V_h -type pattern (Maache-Rezzoug et al., 2008).

81 The objective of the present study was to describe the rheological properties of hydrothermally
82 treated starches in the DIC process in relation to starch granules properties (size and size
83 distribution, swelling behaviour). This study was based on rheological measurements (viscosity
84 and viscoelasticity). These effects were investigated on starches of different origins: standard
85 maize (SMS), waxy maize (WMS), wheat (WTS) and potato (PTS); identical treatments
86 conditions (processing pressure and time) were applied, except for PTS. Lower pressure/time
87 conditions were applied to potato starch due to its higher sensitivity to hydrothermal treatment.

88 **3. Materials and methods**

89 **3.1. Materials**

90 Standard maize starch (SMS), waxy maize starch (WMS, Waxilys 200), wheat starch (WTS)
91 and potato starch (PTS) were supplied by Roquette Frères (Lestrem, France). The moisture
92 content of these starches during the treatment was about 12% wet basis.

93 **3.2. Methods**

94 **3.2.1. *Moisture content***

95 The starch moisture content was determined by air oven at 105 °C during 24 h, according to the
96 A.F.N.O.R (NF V03-707, 2000) standard method and related to the wet basis (% , wb).

97 **3.2.2. *DIC hydrothermal treatment***

98 The equipment and procedure of DIC hydrothermal treatment were largely described in
99 previous studies (Zarguili et al., 2006). During the treatment, 22 g of starch (12.5%, wet basis)
100 disposed in circular containers were placed in the processing vessel (12L) in a layer of 20 cm
101 diameter and 0.5 cm height. An initial vacuum of 50 mbar was established. As demonstrated by
102 Zarguili (2006), this initial vacuum **allows the air resistance to be reduced** and thus facilitates
103 the diffusion of steam into the product, consequently a rapid heating is obtained. Saturated
104 steam is introduced into the vessel at a fixed pressure level (1 to 3 bars) and maintained during
105 a determined processing time. In this study the processing pressure was fixed at 1 bar (100 °C),
106 2 bar (122 °C) and 3 bar (135 °C). The pressurisation is followed by an abrupt decompression
107 towards vacuum (50 mbar). After the vacuum phase, atmospheric air is injected to return to
108 atmospheric pressure for sample recovery. During the treatment, starch is heated by the
109 absorption of latent heat of vapour condensation and its moisture content is increased.

110 3.2.3. *Pasting procedure using the Brabender Viscograph*

111 The DIC treated starches were pasted with demineralised water using a Brabender Viscograph
112 in order to obtain starch pastes under repeatable conditions. The starch concentrations were
113 chosen to lie within the sensitivity range of the Viscograph, depending on the botanical origin
114 of starches. The concentrations used were 6%, 4%, 7% and 2% for SMS, WMS, WTS and PTS,
115 respectively. The suspension was heated at 1.5 °C/min from 50 to 95 °C, then kept for 20 min
116 at the plateau temperature and subsequently cooled down to 70 °C at 1.5 °C/min before
117 immediate characterisation. The starch concentration was checked by drying the suspensions as
118 previously described (3.2.1.).

119 3.2.4. *Granule size distribution*

120 Granule size determination was carried out at room temperature using a Malvern Master Sizer
121 (Malvern Instruments, Ltd) laser scattering analyser with a 300 mm Fourier cell (range 0.05-
122 879 µm). The starch dispersion was first diluted (1/10) with demineralised water at 20°C before
123 and immediately after the pasting procedure in the Brabender Viscograph, and then dispersed
124 into the sample dispersion unit (1ml/100ml water). The measure was repeated three times. The
125 volume distribution was obtained according to the Mie scattering theory (Loisel et al., 2006).
126 From each distribution, the median volume diameter ($D_{v,0.5}$) was presented and the swelling
127 ratio was defined as $(D/D_0)^3$, with D and D_0 the median diameters of treated and native starch,
128 respectively (Nayouf et al., 2003); the size distribution was evaluated using the dispersion
129 index referred to as the span, by the following equation:

$$130 \text{ Span} = \frac{D(v,0.9) - D(v,0.1)}{D(v,0.5)} \quad (\text{Eq.1})$$

131 3.2.5. *Rheological properties*

132 Flow behaviour and viscoelastic properties of starch pastes were measured at 60 °C (to avoid
133 retrogradation) using a controlled stress rheometer (TA Instrument AR1000) with the
134 cone/plate geometry (6 cm/2°). The starch dispersions at 60 °C were poured onto the preheated
135 plate of the rheometer, and then covered by a thin layer of paraffin oil on the edge of the
136 sample to avoid evaporation. For flow measurements, an up-down shear scan from 0 to 660 s⁻¹
137 (4 min) was linearly applied, followed by a logarithmic stepwise decrease from 660 to 0.01 s⁻¹,
138 after equilibrium for each shear rate. The oscillatory tests at 60 °C were carried out on a new
139 aliquot at 4% strain (linear viscoelastic range). The frequency range investigated was from 0.5
140 to 100 rad/s.

141

142 4. Results and discussion

143 4.1. Granule size distribution

144 The size distribution of starch granules was carried out before (Figure 1a) and after pasting
145 (Figure 1b) in the Brabender Viscograph. Table 1 presents the variation of the median diameter
146 $D_{V,0.5}$, the swelling ratio $(D/D_0)^3$ and the span, which measures the volume distribution width
147 of starch granules, for SMS, WMS, WTS and PTS.

148 Before pasting the native starches exhibit a narrow size distribution of the granules, the median
149 diameter lying between 12.9 for SMS, the smaller starch granules, to 44.6 μm for PTS the
150 larger ones with also a minor peak at approximately one micron. These values correspond to
151 the usual starch granule size distribution. For DIC treated starches, the size distribution curves
152 before pasting were shifted towards higher sizes and broadened as increasing DIC conditions,
153 with large differences depending on botanical origin: SMS being more prone to swell than
154 WMS and WTS showing a dramatic increase at 3bar/5min. For PTS only slight modifications

155 were observed due to the low intensity of the DIC conditions. A progressive increase of the
156 median diameter with the intensity of the treatment is attested for all starches. The span values
157 increased for SMS, WMS and WTS, after DIC treatment reflecting a widening of the granule
158 size distribution. This was particularly important for SMS (Table 1) and is probably due to the
159 presence of a third peak at approximately 200 microns (Figure 1) corresponding to aggregates
160 of starch granules. The different evolution of the swelling ratio $(D/D_0)^3$ clearly underlines the
161 differences between starches: SMS and WTS present the highest swelling capacities at
162 3bar/5min of 105.7 and 327.6, respectively. Such a behaviour, particularly for WTS, reflects
163 the cold swelling of DIC treated starch granules; it is not mentioned in the literature for HMT
164 treated starches and has been ascribed to partial loss of cristallinity and subsequent enhanced
165 capacity to hydration (Loisel et al., 2006).

166 After pasting, the size distribution curves (Figure 1) of all the native starches exhibit a shift
167 towards larger sizes as expected. The 1bar/60min treated starches, SMS, WMS and WTS,
168 present the same distribution curve as the native ones with smoothing of the minor peak for
169 WMS. But the 2bar/60min and 3bar/5min treated SMS and WMS show the reverse tendency: a
170 shift towards a lower starch granules size. For SMS and WMS the minor peak at one micron
171 was converted into a larger one, at approximately 5 μm , which disappeared for the most severe
172 conditions for WMS. This peak may be attributed to a population of small starch granules that
173 swell upon pasting or to the disruption of larger ones. The median diameters $D_{V,0.5}$ (Table 1)
174 increase for native starch **after pasting** as expected (from 12.9 to 41.1 μm , 14.3 to 32.5 μm ,
175 19.8 to 36.6 μm and 44.6 to 112.3 μm) for SMS, WMS, WTS and PTS, respectively. **The DIC**
176 **treated SMS and WMS starches present similar sizes to the native ones for the lowest DIC**
177 **conditions (1bar/60min). For medium and high DIC conditions a progressive decrease is**
178 **observed: the swelling ratio reaches 0.4 for SMS and WMS at 3bar/5min.** This modification
179 can be ascribed to concomitant processes of swelling and disruption of starch granules

180 encountered during the pasting process. For DIC treated SMS and WMS the disruption
 181 phenomenon may prevail owing to the sensitivity of starch granules induced by the treatment.
 182 WTS exhibited an outstanding behaviour, by increasing the size of starch granules for the most
 183 severe condition (swelling ratio 1.93 for 3bar/5min). These modifications of the starch granules
 184 size distribution by DIC treatment will obviously affect the rheological properties.

185 **4.2. Rheological properties**

186 Figure 2 presents the rheograms of native and DIC treated starches of SMS, WMS, WTS and
 187 PTS. The flow curves are typical of shear-thinning fluids, except the ones of samples treated at
 188 2bar/60min and 3bar/5min for SMS, 3bar/5min for WTS and at 1.5bar/5min for PTS. We also
 189 observe the persistence of the thixotropic behaviour of the starches, which may result from a
 190 disruption of starch granules aggregates under shearing. This phenomenon appeared less
 191 pronounced when the treatment conditions increased and disappeared for samples treated at
 192 3bar/5min for SMS and 1.5bar/5min for PTS.

193 The Herschel-Bulkley equation (Eq.2) was applied satisfactorily from the equilibrium curves
 194 (not presented in Figure 2) according to Eq. (2):

$$195 \quad \tau = \tau_0 + k \dot{\gamma}^n \quad (\text{Eq.2})$$

196 τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), τ_0 is the yield stress (Pa), K is the
 197 consistency index ($\text{Pa}\cdot\text{s}^n$) and n is the flow behaviour index (dimensionless).

198 The values of the flow parameters (τ_0 , K, n) and the apparent viscosity for 1s^{-1} are given in
 199 Table 2. We observe shear-thinning behaviour ($n < 1$) with a yield stress for all the native and
 200 treated starches except at 2bar/60min and 3bar/5min for SMS, 3bar/5min for WTS, and
 201 1.5bar/5min for PTS. For these DIC conditions, the rheological behaviour of treated starches
 202 tended towards a Newtonian one with increasing flow behaviour index.

203 For WMS and WTS the flow behaviour index remains almost constant for all the process
204 conditions. For all starches the increase of the process conditions causes a decrease of the yield
205 stress and of the apparent viscosity except for WTS.

206 In Table 2 are presented the values of the storage modulus (G'), and the loss modulus (G'')
207 measured at 60 °C. The suspensions of native starches exhibited the behaviour of a weak gel
208 with $G' > G''$ and G' almost independent of frequency (mechanical spectra, not shown).

209 The storage modulus G' sharply decreased for SMS as the process conditions became more
210 intense, while the decrease was more progressive for WMS. This effect of the DIC process on
211 the viscoelasticity of SMS and WMS starch suspensions agrees with previous results (Loisel et
212 al., 2006). WTS is the only starch which behaved in a different way, exhibiting an increase of
213 the storage modulus with the processing conditions.

214 Considering the effect of the treatment on the global properties of the starch suspensions, we
215 can observe the same evolution between the rheological parameters (yield stress, viscosity,
216 storage modulus, Table 2) and the size of the starch granules after pasting (Table 1): a tendency
217 to a decrease for SMS, WMS and PTS and to an increase for WTS with the intensity of the
218 treatment. But no direct relationship can be drawn between these two characteristics as the
219 volume fraction of starch granules is not taken into account. It is well known that the
220 rheological behaviour of a pasted starch suspension is the result of two main characteristics: the
221 viscosity of the continuous phase and the volume fraction of the dispersed phase constituted by
222 the starch granules (Doublier et al., 1987). The concentrations of the starch suspensions used in
223 that study are very close to the packing concentration described by Steeneken (1989): i.e. the
224 suspension can be assimilated to a packing of swollen starch granules that are responsible for
225 the overall rheological properties of the suspensions, the contribution of the continuous phase
226 being minored. In such a concentrated system, the storage modulus indirectly measures the
227 rigidity of the swollen granules. The decrease of the storage modulus for SMS and WMS

228 resulting from the intensity of the treatment may reflect either a loss of rigidity of starch
229 granules; or more probably a decrease of their volume fraction.

230 The DIC process presents some similarities with the HMT treatment as it is conducted at low
231 moisture content between 15 and 20% for DIC (depending on the pressure) compared to the
232 30% usually used for HMT. All the authors state a decrease of the swelling factor (generally
233 expressed as the volume of swollen granules to the volume of the dry starch) and of the
234 Brabender viscosity after pasting and for SMS (Chung et al., 2009) and in a lesser extent for
235 WMS (Hoover and Manuel, 1996; Gunaratne and Corke, 2007). PTS presents the greatest
236 sensitivity to the HMT treatment according to these two characteristics (Gunaratne and Hoover,
237 2002) while WTS exhibits a decrease of the swelling factor but a minor viscosity loss
238 (Gunaratne and Corke, 2007) or even a slight increase of the viscosity after pasting (Hoover
239 and Vasanthan, 1994). The effect of the DIC treatment on the rheological properties of starch
240 suspensions seems similar to a certain extent to the one of HMT treatment.

241 **5. Conclusion**

242 This study has shown that the rheological and morphological properties of starches from
243 different botanical origins, standard maize (SMS), waxy maize (WMS), wheat (WTS) and
244 potato (PTS), are influenced to a different extent by the processing conditions applied during
245 the DIC treatment. The PTS is more sensitive to the treatment than other starches, whereas
246 WMS and WTS are more resistant. When the processing treatments are intense the size
247 distributions of the starch granules and the rheological properties of starch suspensions vary.
248 We observed a reduction in swelling for SMS and WMS starch granules after pasting which
249 was ascribed to their prevailing disruption. For WTS the reverse result was observed. The
250 rheological behaviour tends to Newtonian behaviour ($n=1$), except for WMS, with a decrease
251 of the yield stress and the apparent viscosity as the processing conditions increase. **The**

252 **rheological properties are related to** the evolution of the size of starch granules with the DIC
253 treatment.

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332

Figures Captions

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334

335 **Figure 1:** Size distribution of native and DIC treated SMS, WMS, WTS, and PTS starches: (a)
336 before pasting and (b) after pasting.

337

338 **Figure 2:** Flow curves of native and DIC treated starch dispersions measured at 60 °C after
339 pasting, with starch concentration of 6%, 4%, 7% and 2% for SMS, WMS, WTS and PTS,
340 respectively.

341

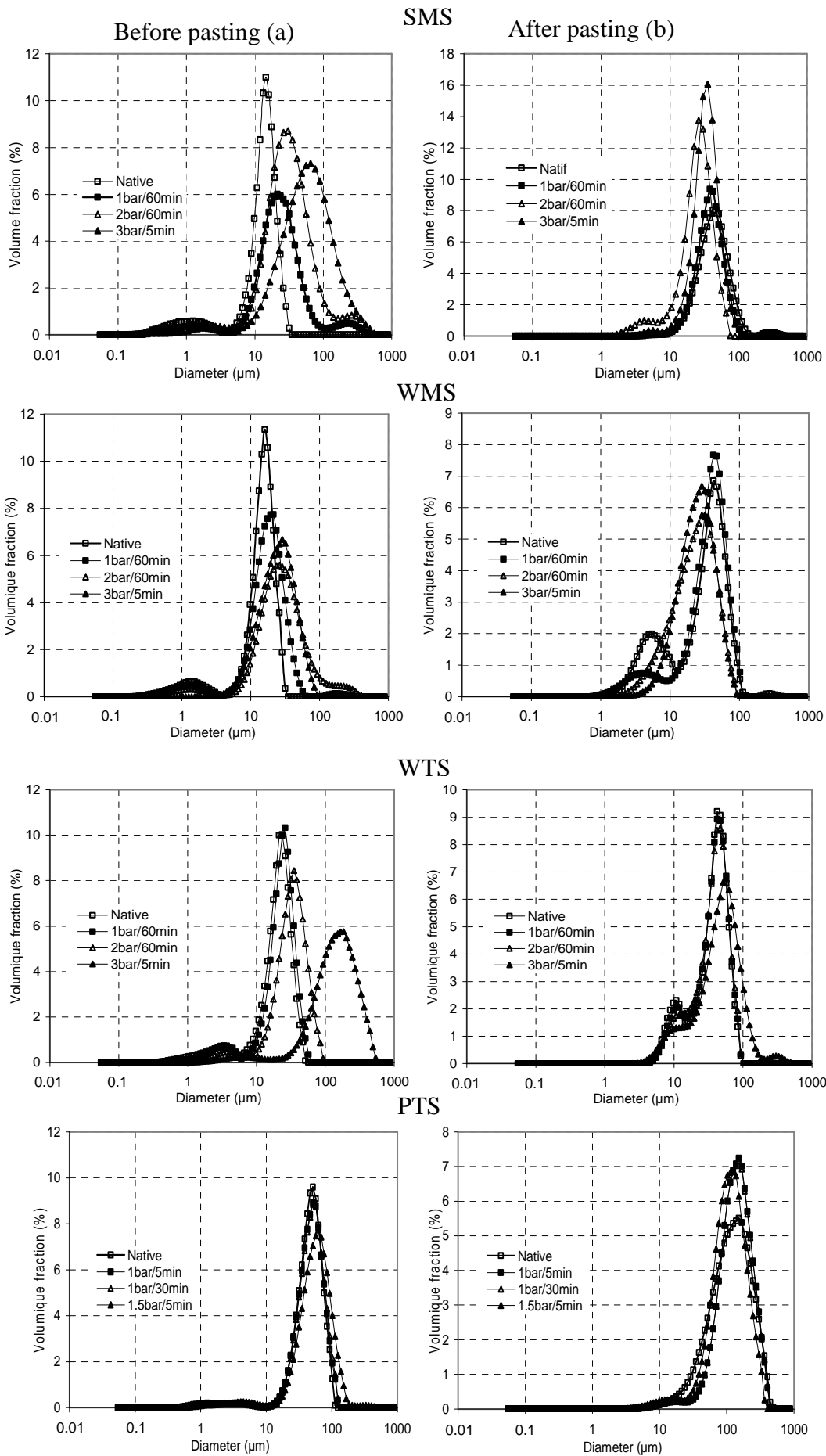
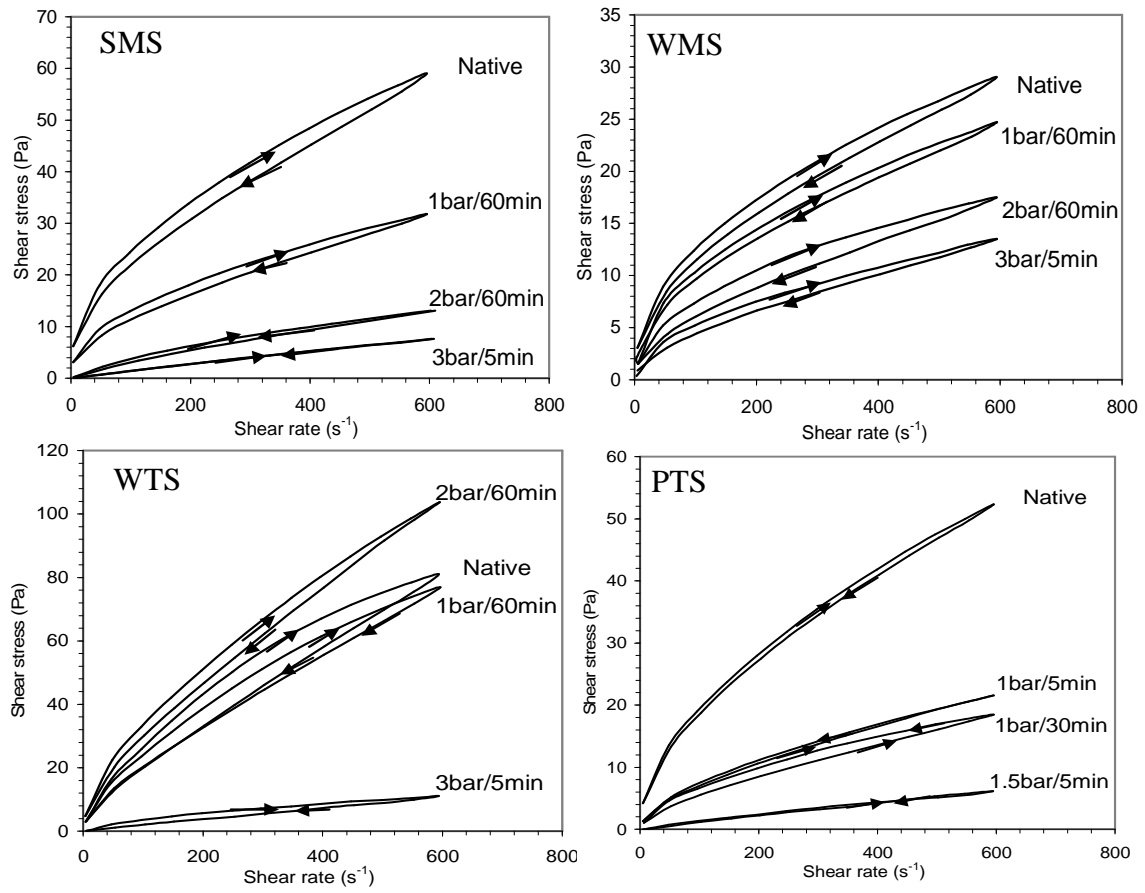


Figure 2



344 **Table 1:** Particle size characteristics of SMS, WMS, WTS and PTS after DIC treatment.

345 (standard deviation of $D_{v,0.5} = 0.3 \mu\text{m}$)

346

Starch source	DIC conditions Pressure level/ processing time (bar/min)	Granulometry					
		Before pasting			After pasting		
		$D_{v,0.5}$ (μm)	$(D/D_0)^3$	Span	$D_{v,0.5}$ (μm)	$(D/D_0)^3$	Span
SMS	native	12.9	1.0	1.4	41.1	1.0	1.3
	1/60	19.3	3.3	1.5	39.3	0.9	1.2
	2/60	27.7	9.9	2.4	23.8	0.2	1.3
	3/5	61.0	105.7	2.5	29.6	0.4	1.8
WMS	native	14.3	1.0	1.1	32.5	1.0	1.8
	1/60	17.1	1.2	1.4	36.1	1.4	1.7
	2/60	25.3	5.5	2.4	22.5	0.3	1.8
	3/5	39.5	21.1	1.8	23.7	0.4	1.5
WTS	native	19.8	1.0	1.2	36.6	1.0	1.3
	1/60	22.2	1.4	1.2	36.8	1.0	1.3
	2/60	30.5	3.6	1.4	36.7	1.0	1.4
	3/5	136.5	327.6	1.8	45.6	1.9	1.8
PTS	native	44.6	1.0	1.2	112.3	1.0	1.9
	1/5	45.8	1.1	1.2	114.8	1.1	1.5
	1/30	46.4	1.1	1.2	114.4	1.1	1.5
	1.5/5	54.1	1.8	1.4	104.9	0.8	1.5

347 **Table 2:** Herschel-Bulkley parameters and viscoelastic properties of SMS, WMS, WTS and
 348 PTS pasted suspensions after DIC treatment.

Starch source	DIC conditions	Flow behaviour 60°C				Viscoelasticity (60°C ;6.3 rad/s)		
	Pressure level / processing time (bar / min)	τ_0 (Pa)	K (Pa.s ⁿ)	n	η_a (Pa.s)	G' (Pa)	G'' (Pa)	Tan(δ)
SMS ^a	native	2.28	1.39	0.57	3.68	126.7	16.6	0.13
	1/60	0.68	0.72	0.58	1.41	115.4	13.4	0.12
	2/60	0.00	0.04	0.91	0.04	0.43	0.16	0.37
	3/5	0.00	0.01	1.00	0.01	3.12	0.91	0.29
WMS ^b	native	0.70	0.88	0.53	1.58	1.96	1.06	0.54
	1/60	0.71	0.81	0.52	1.52	1.69	0.93	0.55
	2/60	0.31	0.26	0.62	0.57	1.12	0.74	0.66
	3/5	0.36	0.58	0.54	0.95	1.20	0.90	0.75
WTS ^c	native	0.95	0.44	0.78	1.39	21.7	11.2	0.52
	1/60	0.87	0.75	0.70	1.63	30.1	12.8	0.45
	2/60	1.00	0.87	0.72	1.87	26.9	10.5	0.39
	3/5	0.00	0.03	0.88	0.03	63.5	12.4	0.19
PTS ^d	native	0.77	1.28	0.57	2.05	9.70	6.4	0.66
	1/5	0.06	0.47	0.60	0.53	3.90	2.5	0.64
	1/30	0.02	0.15	0.71	0.17	4.10	2.7	0.66
	1.5/5	0.00	0.02	0.89	0.02	0.34	0.04	0.11

349 ^a 6% (w/w) SMS suspension; ^b 4% (w/w) WMS suspension; ^c 7% (w/w) WTS suspension and ^d 2% (w/w)
 350 PTS suspension; τ_0 :yield stress ; K : consistency index; n : flow behaviour index (τ_0 , K and n were
 351 determined from Herschel-Bulkley model); η_a :apparent viscosity measured at 1s⁻¹.