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Competitive adsorption of PAM and HPAM on Siliceous Material

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Enhanced oil recovery (EOR)

29 **ABSTRACT**

30 The present work aims at studying the outcome and kinetics of competitive adsorption
31 between low and high molar mass chains of neutral polyacrylamide (PAM) or partially
32 hydrolyzed polyacrylamide (HPAM) in aqueous solution at the surface of siliceous material.
33 Monodisperse neutral and charged polymers, PAM and HPAM, were synthesized by
34 RAFT/MADIX polymerization and their adsorption alone or in competitive process was
35 studied. The analysis of adsorption measurements were carried out quantitatively by size
36 exclusion chromatography which allows for distinguishing the relative adsorption of the
37 chains depending on their molar masses. The effect of the average molar mass, dispersity as
38 well as the kinetics of the displacement of pre-adsorbed polymer chains onto the surface by
39 longer chains was investigated. We evidenced that both PAM and HPAM exhibit the same
40 trend. Close to surface saturation, the high molar mass chains desorb polymer chains of lower
41 molar mass. Moreover, by mixing different monodisperse polymer we were able to model the
42 behavior of the polydisperse systems usually encountered in practical applications. By
43 following adsorption over time, our results show that while low molar mass polymers diffuse
44 rapidly and adsorb first, they are displaced by high molar mass ones once they reach the
45 surface. This result remains unchanged even if the low molar mass chains are added several
46 hours before the higher ones showing that there is no kinetic limitation to the displacement of
47 low molar mass PAM and HPAM by higher molar mass ones. The understanding and
48 prediction of this complex competitive adsorption behavior over time is of utter importance
49 for the control of the mechanism of action of these polymers notably in industrial processes.

50

51

52 **INTRODUCTION**

53 The competitive adsorption of polymers, i.e. the exchange of macromolecules onto
54 solid surfaces, a phenomenon occurring in numerous application where polymer adsorption is
55 involved, has been widely studied since the 1970s. Understanding and controlling the
56 competitive adsorption between polymer chains of different average molar mass is of great
57 interest in lots of industrial processes.

58 Indeed, polymers, and in particular neutral (PAM) or partially hydrolyzed (HPAM)
59 polyacrylamides are used in a wide range of industrial applications, such as water treatment
60 by flocculation of particles¹, soil stabilization,^{2, 3} agriculture,⁴ cement flow control,⁵⁻⁷ and last

61 but not least, in the field of enhancement oil recovery (EOR) where acrylamide based
62 polymers are massively used mainly to increase the viscosity of the injected fluid.⁸ The study
63 of competitive adsorption is of particular interest in this last case where PAM or HPAM of
64 very high average molar mass with broad molar mass distributions are involved. Indeed,
65 during oil recovery, injection of such polymers in the injection well leads to a rapid injectivity
66 loss which negatively impacts the process. Despite its tremendous effect on the ability or not
67 to effectively recover the oil from the field, the origins of this injectivity loss such as
68 hydrodynamic retention, mechanical entrapment or adsorption are still a matter of debate.
69 Recently, Bessaies-Bey et al. showed that polymer adsorption is the leading cause for the loss
70 of injectivity sometimes suffered by the oil industry as it can lead to permeability reductions
71 by orders of magnitudes.⁹ Thus, the characterization of the adsorption of PAM or HPAM onto
72 siliceous materials and particularly the competition between polydisperse species is a key
73 point to reduce those perturbing effects. Although, polymer adsorption in general has been
74 extensively studied in the literature both at the experimental and theoretical level, to the best
75 of our knowledge, the competitive adsorption of PAM or HPAM of different lengths on
76 siliceous materials has been never investigated which is surprising considering their intensive
77 use in various industrial contexts.

78 Concerning the competitive adsorption of polymers having different average molar
79 masses, three main cases emerge from the literature: uncharged macromolecules¹⁰⁻¹⁵ and
80 polyelectrolytes in high¹⁶ and low^{16,17} salt content medium. Even if it is globally admitted that
81 in the first two cases longer polymer chains preferentially adsorb to the substrate following
82 entropic considerations¹⁸ while in the third case it is the shorter polymer chains that are
83 preferred because the system is then driven by the electrostatic energy balance, some
84 questions remain:

85 (i) Firstly, regarding the experimental works cited above, the kinetics of
86 desorption/adsorption depends on several parameters such as the average molar mass and the
87 mass dispersity, the structure of the polymer chain, its chemical nature and the mechanism of
88 adsorption. Reported experiments on the adsorption of polyacrylamide on natural quartz
89 revealed that polymer adsorption is due to the formation of multiple hydrogen bonding
90 between the polymer chains and both silanol and aluminol groups present on the natural
91 quartz surface.^{9, 19} Then the repartition and proportion of anchoring sites at the surface of
92 substrate may play a major role on the competition between species. In this particular case,
93 does the adsorption of larger macromolecules still prevail?

94 (ii) Moreover in EOR applications, most of the so-called polyacrylamides are in fact
95 partially hydrolyzed and weakly negatively charged. In this intermediate case between the
96 neutral polymer and polyelectrolyte case, what is the impact of the average molar mass of the
97 polymer on adsorption keeping the density of anionic groups constant?

98 (iii) Most of the experimental studies concerning competitive adsorption cited above
99 have been performed in organic solvent with specific conditions which are far from the
100 industrial reality. For instance, in applications concerning PAM/HPAM adsorption to natural
101 quartz, water is the reference solvent which can complicate the system because it interacts
102 both with the polymer and the oxide.

103 The present work aims at addressing carefully the issue of PAM/HPAM adsorption on
104 silicates by studying the outcome and kinetics of competitive adsorption between low and
105 high molar mass PAM or HPAM in aqueous solution at the surface of model siliceous
106 material. We first present a method of analysis of adsorption experiments based on Size
107 Exclusion Chromatography (SEC) which allows for a quantitative determination of the
108 relative amount of adsorbed polymer chains of different molar masses. Adsorption
109 experiments were performed using monodisperse PAM and HPAM in a broad range of molar
110 masses from 10 to 1000 kg/mol. These polymers, synthesized by RAFT/MADIX
111 polymerization,²⁰ allowed us not only to investigate the adsorption behavior of the polymer
112 alone in solution but also to model the behavior of industrial polymers (high dispersity) by
113 mixing several monodisperse polymers. Finally, we focused on the kinetics of displacement
114 of polymer chains pre-adsorbed onto the surface as a function of the pre-adsorption time.

115

116 **MATERIALS AND METHODS**

117 **Materials.** *Siliceous materials.* Crystallized natural quartz (99.5 % SiO₂, 0.5 % Al₂O₃),
118 named Sikaisol was acquired from Sika (Specific area $S=0.56$ m²/g, determined by BET
119 Nitrogen adsorption; bulk density $\rho=2650$ kg/m³; mean particle diameter $D=50$ μ m),

120 *Polymers.* Acrylamide (AM) (40 % aqueous solution) and acrylic acid (AA) (99 %) were
121 purchased from Sigma-Aldrich. Well-defined PAMs and P(AM-*st*-AA)s with different
122 average molar masses and anionicity were synthesized by Reversible Addition Fragmentation
123 chain Transfer / Macromolecular design by interchange of xanthates (RAFT/MADIX)
124 polymerization according to a modified version of the protocol we previously reported.²⁰
125 Using a low molar mass ($DP_n \sim 7$) polyacrylamide macro-RAFT/MADIX agent, the
126 polymerization of Am or Am/AA mixtures was performed at 25 °C at 20 wt% in water for 2h,

127 using the ammonium persulfate (APS) / sodium formaldehyde sulfoxylate dihydrate redox
128 initiator. The pH of the reaction mixture was adjusted to 6 prior to polymerization. The
129 resulting polymer was freeze-dried before storage in order to remove water and traces of
130 residual monomer. The characteristics of the polymers such as average molar mass, dispersity
131 and the degree of anionicity are gathered in **Table 1**. The synthesized statistical polymers
132 P(AM-*st*-AA) will be assimilated to hydrolyzed polyacrylamide and noted HPAM-X where X
133 indicates the average molar mass (**Table 1**).

134 *Adsorption experiments.* 4 g of quartz particles were first mixed in a bottle with 10 mL of
135 polymer solutions with concentrations ranging from 10 ppm to 200 ppm. Experiments were
136 conducted at the pH of pure water in presence or absence of CaCl₂. Adsorption experiments
137 were conducted at a solid/liquid ratio of 0.4. The bottles were left rolling at constant
138 temperature (23 °C) during 2 hours. The quartz particles were then removed by centrifugation
139 at 6000 g for 15 min to extract the interstitial solution. The supernatant was analyzed with one
140 of the methods described below, namely Total Organic Carbon (TOC) and/or Size Exclusion
141 Chromatography (SEC).

142 *Total Organic Carbon (TOC).* Total Organic Carbon experiments were performed on a TOC-
143 VCSH (Shimadzu). The TOC analyzer was first calibrated with reference polymer solutions
144 of known concentrations and by analyzing the liquid phase of the quartz suspension without
145 any polymer. By comparison between this reference value and the measured organic carbon
146 amount in the water extracted from polymer adsorption experiments, the amount of polymer
147 adsorbed on natural quartz was computed. This technique assumes that the difference between
148 polymer concentration before and after contact with quartz particles is only owed to
149 adsorption at the surface of particles.

150 *Size Exclusion Chromatography (SEC) and data treatment.* Size exclusion chromatography
151 was performed on a Malvern Viscotek TDA 302 system triple detector equipped with three
152 OH-pak SB-806M HQ columns in series and a guard column. The mobile phase is an aqueous
153 solution at 0.2 M NaNO₃ and the flow-rate is 0.7 mL/min. 100 µL of each sample is passed
154 once in the set of columns before detection. The number- and weight average molar masses
155 (respectively M_n and M_w) and dispersity ($D=M_w/M_n$) were derived from a universal calibration
156 curve based on poly(ethylene oxide) standards from Malvern. Compared to TOC analysis,
157 SEC experiments allows both to distinguish and quantify the polymers depending on their
158 average molar mass.

159 The chromatograms obtained from the measured refractive index as a function of the retention
160 volume are fitted with log normal distribution in order to extract the area under the
161 chromatograms which was further used to estimate the concentration of a given polymer in a
162 solution containing polyacrylamide with different average molar mass.²¹ As an example, a
163 SEC chromatogram of a polymer solution containing PAM-10K and PAM-1000K is shown in
164 **Figure S1** in Supporting Information. The area under each peak can be correlated to its
165 concentration through pre-determined calibration curves.

166

167 **Table 1:** Main characteristics of PAM and HPAM used in this study

Designation	Anionicity (%)	M_w (kg/mol)	M_n (kg/mol)	\bar{D}
PAM-10K	0	17	16	1.04
PAM-100K	0	167	150	1.11
PAM-1000K	0	1284	1222	1.05
HPAM-10K	10	17	16	1.04
HPAM-100K	10	181	166	1.09
HPAM-1000K	10	817	750	1.09

168

169

170

171

172 **RESULTS AND DISCUSSION**

173 *Adsorption of PAM/HPAM on natural quartz*

174 We first quantified the amount of adsorbed polymer on natural quartz of PAM in pure
175 water and anionic HPAM in CaCl₂ solution with TOC experiments. As shown in **Figure 1**,
176 the amount of adsorbed polymer steeply increased with the polymer concentration with values
177 of the initial slope varying from 40 to 300 ml/m² characteristic of a high affinity between the
178 polymer and the particle surface.^{22, 23} This increase was immediately followed by an
179 adsorption plateau at high polymer concentration, which corresponds to full surface coverage.
180 It is now well established that the driving force of the adsorption of acrylamide-based
181 polymers on siliceous materials is the formation of multiple hydrogen bonds between the
182 amide groups of the polymers and hydroxyl groups on the silica surface,²⁴ and this adsorption
183 is exacerbated by the presence of aluminol groups.⁹ The amount of adsorbed polymer can also

184 be impacted by the physicochemical parameters of the polymer/particle system (pH,
 185 temperature, ...) and notably the presence of electrolyte in solution which can decrease the
 186 solubility of the polymer chains in solution and consequently increase the adsorbed amount.
 187 In our two systems, PAM/H₂O and HPAM/H₂O/CaCl₂, both polymer chains are in good
 188 solvent as reported in the literature and in **Figure S2** (Supporting information) respectively.
 189 At the pH of the suspensions (pH=6), both the HPAM and the silica surface groups are
 190 negatively charged. However, during the adsorption of HPAM on natural quartz, the presence
 191 of CaCl₂ screens the electrostatic repulsions between the HPAM and the silica surface. Hence,
 192 HPAM in CaCl₂ solution behaved, as expected, similarly to PAM in pure water.
 193 We moreover note that the maximum adsorption plateau, Γ_{\max} , increases when the average
 194 molar mass of the polymer increases as shown in **Figure 1c**. Indeed, for both PAM/H₂O and
 195 HPAM/H₂O/CaCl₂ systems, the maximum adsorption value varies as a function of molar
 196 mass following a power law with a power exponent of 0.14. This value is consistent with the
 197 reported values for uncharged macromolecules adsorbed on silica.^{14, 22, 25}
 198
 199

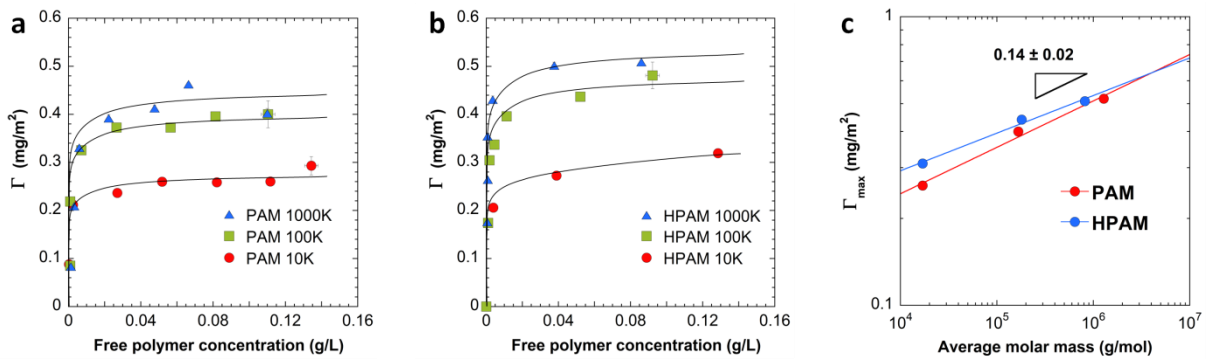


Figure 1: Adsorption isotherms on natural quartz for (a) PAM in pure water and (b) HPAM in CaCl₂ solution (I=0.035 M). The lines are guides for the eyes (c) Maximum adsorption amount, Γ_{\max} , as a function of the average molar mass of acrylamide-based polymers.

200

201 ***Mixing monodisperse PAM or HPAM of different average molar masses: Towards a better***
 202 ***understanding of competitive adsorption of industrial polymers***

203 This part aims at understanding the effect of the dispersity of industrial PAMs or
 204 HPAMs on adsorption by modelling them with a well-controlled distribution of molar masses
 205 reconstructed from highly monodisperse batches (see **Table 1**). Experiments were conducted
 206 with either a mixture of PAM-10K, PAM-100K and PAM-1000K or HPAM-10K, HPAM-

207 100K and HPAM-1000K, with the same weight fraction for each component. We chose to
208 study the competitive adsorption of the three polymers by mass and not by number of chains
209 for reasons of SEC sensitivity and viscosity of solution. Indeed conducting the study in terms
210 of number of chains would result in a difference of two orders of magnitude between the mass
211 concentrations between polymers having the lowest and the highest average molar mass.
212 Knowing both M_n and M_w of each polymer, it is possible to compute the dispersity, \mathcal{D} , of the
213 polymer mixtures. Dispersities of 11.4 and 7.9 were targeted, for PAM and HPAM mixture
214 respectively, which is fairly representative of what can be used in industrial applications. The
215 same adsorption protocol as for the individual polymer adsorption experiments was followed.
216 Natural quartz particles are mixed with a solution of polymers mixture of varying
217 concentrations for 24 hours at a solid to liquid ratio of 30 wt%. After centrifugation, the
218 supernatant was then characterized with SEC. **Figure S3** in Supporting information shows the
219 chromatogram of supernatant (i.e. non adsorbed polymer solution) obtained with a refractive
220 index detector for different initial concentrations of PAM-10K, PAM-100K and PAM-1000K
221 mixtures. The fitting of these chromatograms allows to determine the quantities of each mass
222 distribution remaining in solution and consequently the quantities adsorbed onto the surface.
223 Thereby the competitive adsorption of each polymer solutions containing three monodisperse
224 polymers onto natural quartz particles can be plotted. For both polymer mixtures, PAM
225 (**Figure 2a**) and HPAM (**Figure 2b**), the adsorption isotherm could be divided in two parts.
226 First, at low concentrations of polymers, i.e. lower than 0.05 g/L, all species present in
227 solution adsorbed on particles because there is enough space at the particles surface. This
228 interpretation was supported by the chromatograms of the supernatant (**Figure S3** in
229 Supporting information) where no polymers are detected in regards to the detection limits of
230 the SEC technique. As illustrated in **Figure 2a** and **2b**, when increasing the polymer
231 concentration, the adsorbed amount for the two polymers having the lowest average molar
232 masses progressively decreased and tended toward zero while the polymer with the higher
233 molar mass continued to adsorb onto particles until the saturation of the particles surface
234 made it impossible to absorb more polymer chains onto it. In the case of the PAM mixture, we
235 observed that the adsorption of the PAM-1000K reached the same adsorption value, $\Gamma_{\max} \sim$
236 0.5 mg/m^2 as the one obtained by TOC for the polymer alone (**Figure 1a**). However, for the
237 HPAM mixture it is worth noting that the adsorption of HPAM-1000K was significantly
238 lower (0.3 mg/m^2) than the one of the polymer alone, $\Gamma_{\max} \sim 0.5 \text{ mg/m}^2$. A possible
239 explanation would be that the ionic strength was too low to fully screen the particles surface
240 charges as previously reported.⁹ Then, electrostatic repulsion occurred either between the

241 particle surface groups and the HPAM polymer or between HPAM adsorbed on the particle
 242 surface and free HPAM chains thus reducing its adsorption. In any case, the adsorption of
 243 polydisperse PAM and partially screened HPAM led to the same behavior, i.e. the adsorption
 244 of the polymer chains having the higher molar mass prevailed considerably over the shorter
 245 polymer chains present in solution. Nevertheless, as shown the **Figure 2a** and **2b**, for both
 246 PAM and HPAM systems some polymer chains with lower molar masses still remained on
 247 the surface.

248 Furthermore, it is also possible to calculate from these data the M_n , M_w and \mathcal{D} values of the
 249 supernatant composition for each concentration of polymer mixtures. To a certain extent,
 250 these mixtures model the properties of a polymer with large dispersity during competitive
 251 adsorption. The respective evolutions of each parameter are highlighted in **Figure 2c**. At low
 252 surface coverage, the supernatant composition was very close from a pure solution of PAM-
 253 10K in terms of M_n and M_w , with a dispersity close to 1. Then the dispersity and both the
 254 number- and weight-average molar mass of the polymer mixture present in the supernatant
 255 increased with concentration meaning that polymer chains having the highest molar mass start
 256 to be present in the supernatant. This is due to the fact that the polymer chains with the
 257 highest molar mass preferentially impact the weight-average molar mass of the polymer
 258 mixture. Finally at higher dosage the macromolecular parameters (M_n , M_w and \mathcal{D}) tended
 259 toward the properties of the initial mixtures (PAM-10K, PAM-100K and PAM-1000K equal
 260 in weight proportions) illustrated by dashed lines in **Figure 2c**. This meant that the surface
 261 was saturated and the polymer chains with different molar mass were present in the
 262 supernatant. These observations were consistent with reported studies showing a modification
 263 of the chromatogram of the supernatant after adsorption of polydisperse polymers on silica
 264 particles.^{14, 26}

265

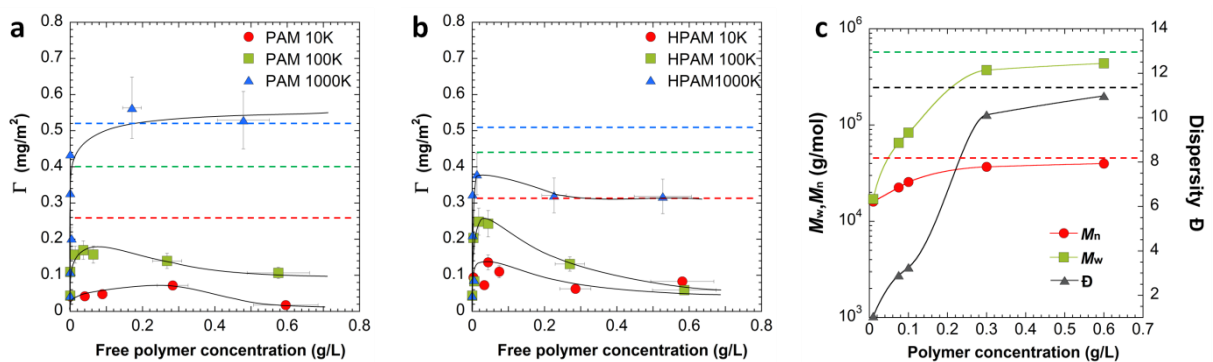


Figure 2: Competitive adsorption on natural quartz of (a) PAM in pure water and (b) HPAM in CaCl₂

solution ($I=0.035$ M) with 24h contact time. The solid lines are guides for the eyes. The dashed lines represent the maximum adsorption value, Γ_{\max} , when the polymer is alone in solution. (c) Evolution of the average molar masses, M_w and M_n , and dispersity D of the supernatant during competitive adsorption on natural quartz of a mixture of PAM-10K, PAM-100K and PAM-1000K as a function of the initial concentration of polymers mixture. The solid lines are guides for the eyes. The dashed lines correspond to the M_w , M_n and D of the initial polymer mixture.

266

267

268 *Adsorption-desorption kinetic aspects*

269 As observed in the previous section, the longer polymer chains, PAM-1000K or
270 HPAM-1000K in electrolyte solution, adsorb preferentially on natural quartz to the detriment
271 of polymer chains of molar masses lower by one or two orders magnitude. However, it should
272 be kept in mind that literature results suggest that regardless of differences in molar masses,
273 kinetics of adsorption/desorption can vary over orders of magnitude depending on the
274 polymer structure, the substrate properties (chemical nature, porosity...) and the resulting
275 adsorption driving force as well as the equilibrium time of the preadsorbed polymer chains.
276 Indeed, Kawaguchi et al. studied by ellipsometry the competitive adsorption onto platinum
277 plate between on the one hand 102 and 775 kg/mol, and on the other hand 422 and 775
278 kg/mol polystyrene in theta conditions.²⁷ The authors reported that the kinetics of
279 displacement by 775 kg/mol polymer chains of 442 kg/mol polystyrene is slower than for 102
280 kg/mol. Then, they noted that the displacement of shorter polymer chains is complete after
281 20h. The same observations have been made by Fu et al. for the competitive adsorption of
282 poly(ethylene oxide) chains having different molar masses on glass.^{12, 28} However, they
283 noticed that short PEO chains become more difficult to displace from the surface when their
284 contact time with the interface or the relative molar mass of the preadsorbed polymer chains is
285 increased.²⁹ Conversely, rapid and total displacement, on the order of several hours, have been
286 also observed in the literature for polystyrene/silica system.^{14, 30} In summary, we can conclude
287 from the literature that the kinetics of displacement of adsorbed polymer chains is highly
288 system dependent.

289 In this section, we thus report the kinetic aspects of competitive adsorption using SEC
290 experiments either by sequential (i.e. by contacting the surface with the shorter polymer
291 chains during a certain period of time prior to injection of the polymer chains with the higher
292 molar mass) or simultaneous coadsorption of two PAM polymers. By this set of experiments,
293 we tried to answer two questions: How fast does the desorption occurs? And how long does it

294 take to reach equilibrium? For that purpose, two competitive adsorption experiments were
295 carried out. First, PAM-10K and PAM-1000K were simultaneously put in contact with natural
296 quartz particles at an initial concentration of 0.2 g/L which corresponds to the saturation
297 regime on the particles surface. Then after a time varying from 5 minutes to several hours
298 after addition of both polymers, the samples were centrifugated and the supernatant
299 characterized with SEC. For the second experiment, the short polymer chains, PAM-10K,
300 were first put in contact with natural quartz particles. Thereafter, two different delayed times
301 of addition of the high molar mass polymer PAM-1000K have been investigated to highlight
302 the effect of contact time, i.e. 2 and 24 hours. Afterwards, after 5 minutes to several hours, as
303 in the previous experiment, the samples were centrifugated and the supernatant characterized
304 with SEC. The results are gathered in **Figure 3**.

305 In the case of coadsorption where both polymers are put simultaneously in contact with
306 natural quartz particles (**Figure 3a**), two regimes were clearly observed. For contact time
307 between the polymers and the natural quartz lower than 30 min, we observed that both
308 polymer chains adsorbed onto the surface. This is due to the fact that shorter polymer chains
309 diffuse much faster than the longer ones and then reach the surface in first.³¹ Then, after
310 around 30 minutes of contact time, the PAM-1000K chains remained adsorbed onto the
311 surface whereas the amount of adsorbed PAM-10K started to decrease. As experimentally
312 reported in the literature by Fu et al. the desorption of short chains from the surface begins
313 only when the mass saturation of the surface reaches the one expected when adsorbing of
314 shorter chains alone, here 0.3 mg/m² for PAM-10K.¹² One hour after the contact time, t_0 ,
315 corresponding to the introduction time of PAM-1000K, the maximum adsorbed amount was
316 reached, i.e. 0.5 mg/m². Surprisingly, the desorption of PAM-10K was not complete even
317 after 24 hours. For neutral polymer such as PAM, displacement of short chain polymers was
318 expected since in theory, the free energy of an adsorbed polymerchain is directly proportional
319 to the polymerization degree and consequently to its molar mass.³² For HPAM, electrostatic
320 considerations complicate the matter but, as we have seen above, their behavior in presence of
321 salts is very similar to the one of a neutral polymer due to charge screening. The fact that
322 some short chain polymer remained adsorbed is more puzzling and remains an open question.
323 It could be due to a slow down diffusion of the small polymers in the larger polymer adsorbed
324 layer or to an additional chemical potential term due to polymers concentration near the
325 surface. **Figure 3b** and **3c** show the delayed competitive adsorption between PAM-10K and
326 PAM-1000K, that is when the long polymer chains PAM-1000K were put in contact with a
327 delay time of $t_0=2h$ and $t_0=24h$ after the introduction of the shorter chains. As soon as the

328 PAM-1000K is added to the sample, PAM-10K started desorbing whereas adsorption of
 329 PAM-1000K increased which means that the contact time between PAM-10k and natural
 330 quartz particles did not play a significant role on the kinetics of displacement of short polymer
 331 chains by the longer ones.

332 Nevertheless, we can notice that in both cases, simultaneous coadsorption (**Figure 2** and
 333 **Figure 3a**) or sequential adsorption (**Figure 3b** and **3c**), a small amount of shorter chains
 334 remain adsorbed on the surface. Two hypothesis can explained this observation. First this
 335 could reflect the occurrence of a few high energy adsorption sites on the natural quartz
 336 surface. This hypothesis is supported by the fact that two kind of adsorption sites are present
 337 on the natural quartz surface investigated in this study, i.e. silanol and aluminol groups.
 338 Indeed, we have previously shown that the presence of aluminol groups on natural quartz
 339 surface further increases the adsorption of acrylamide-based polymers.^{9, 33} This could explain
 340 the fact that some polymer chains still remain adsorbed on the particle surface despite the
 341 presence of polymer chains of higher molar mass. A second tentative explanation could be
 342 that despite the desorption of adsorbed chains by the longer ones, several shorter polymer
 343 chains can occupied the residual surface onto quartz particles and explain the observed
 344 results.

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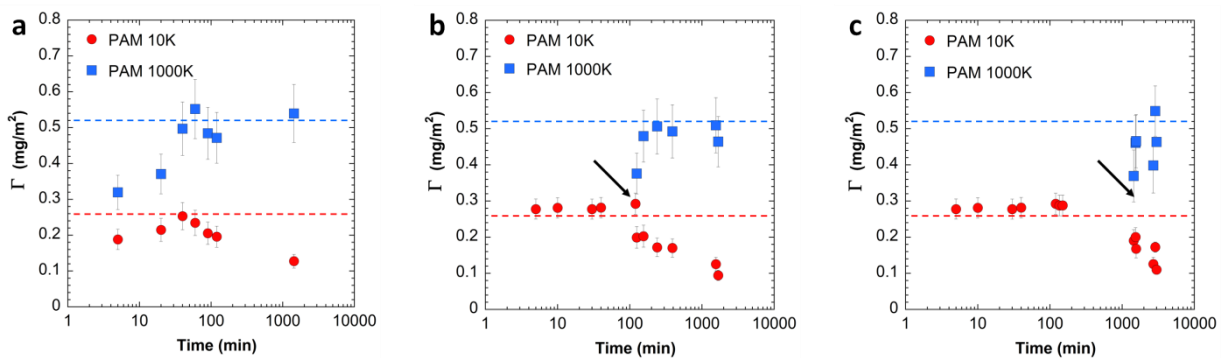


Figure 3: Competitive adsorption in time between PAM-10K and PAM-1000K at 0.2 g/L on natural quartz either by (a) coadsorption ($t=0$) or after a delay of (b) $t=2h$ and (c) $t=24h$. The dashed lines represent the maximum adsorption value, Γ_{max} , when the polymer is alone in solution. The arrow indicates the time (t_0) where the PAM-1000K is put in contact with the natural quartz/PAM-10K system. For the coadsorption, $t_0=0$ min.

348

349 **CONCLUSION**

350 In the present work, thanks to the coupling of size exclusion chromatography
351 technique and the use of well-controlled polymers in size and distribution, we clarified the
352 mechanism of competitive adsorption of PAM and HPAM on natural quartz. We evidenced
353 that neutral and charged polyacrylamide exhibit the same behavior in presence of salts. Once
354 the surface is mass saturated from the point of view of shorter polymer chains, the longer ones
355 start desorbing the short ones. Besides, the contact time between the polymer and the surface
356 did not seem to affect the mechanism involved. Even when the low molar mass chain
357 polymers were added several hours before the higher ones, the outcome of competitive
358 adsorption remained unchanged. However, we observed that even after a long equilibrium
359 time, few polymer chains remained adsorbed onto the surface suggesting either the possible
360 presence of anchoring sites with different adsorption energy or residual surface onto quartz
361 particles. Moreover, by mixing different monodisperse polymers we were able to model a
362 polydisperse system close to the real polydisperse macromolecules effectively encountered in
363 industrial contexts.

364

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