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Research paper

Influence of cationic cellulose structure on its interactions with sodium dodecylsulfate: implications on the properties of the aqueous dispersions and hydrogels

R. Rodríguez, C. Alvarez-Lorenzo, A. Concheiro*

Departamento de Farmacia y Tecnología Farmacéutica, Universidad de Santiago de Compostela, Santiago de Compostela, Spain

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Abstract

The interactions of sodium dodecylsulfate (SDS) with the aqueous dispersions and the chemically cross-linked hydrogels of two cationic hydroxyethylcelluloses, polyquaternium-4 (PQ-4) and polyquaternium-10 (PQ-10), commonly used in cosmetics and in topical drug delivery devices, were analyzed. This surfactant was chosen not only for its interest as excipient, but also as a model of the amphiphilic behavior shown by many drugs. In aqueous dispersions, the interaction process was studied through transmittance, surface tension, fluorescence, microcalorimetry titration, viscosity and oscillatory rheometry measurements. The ammonium/sulfate groups ratios at the critical aggregation concentration (0.05% SDS) were 2.61 for PQ-4 and 4.02 for PQ-10; while at the saturation concentration (0.25% SDS), these ratios decreased to 0.52 and 0.80, respectively. The binding process, through ionic and hydrophobic interactions, was strongly exothermic in both water and aqueous NaCl 0.9% solution, which indicates that the salt did not modify the interaction. PQ-4/SDS dispersions had, for all SDS concentrations, higher viscous (G'') and, especially, elastic (G') moduli than the polymer solution. The maxima in G' and G'' (four orders of magnitude greater than PQ-4 only solutions) were observed at the SDS concentrations in which the ammonium/sulfate groups ratio is close to 1. PQ-10/SDS dispersions behaved very differently and, near the neutralization point, the precipitation of the system caused G'' to decrease abruptly, and G' to disappear. The contrasting behavior of the two cationic celluloses may be attributed to their structural differences; PQ-4 has less ammonium groups, in small chains grafted to the cellulose backbone, and more free hydroxyethyl substituents than PQ-10. Therefore, although the neutralization of charges causes the formation of a neutral polyampholyte, the presence of the free hydrophilic hydroxyethyl groups in PQ-4 avoids the precipitation of the aggregates and contributes to the establishment of a three-dimensional network. In contrast, in PQ-10, the ammonium groups are directly bonded to the hydroxyethyl substituents and, in the aggregation process, they may be included in the polyampholyte complex, contributing to the precipitation. This different behavior was easily seen in the surfactant-induced shrinking of the hydrogels around the charges neutralization. Although the SDS binding isotherms were very similar, PQ-10 hydrogels decreased their volume up to 20 times at the neutralization point, while PQ-4 hydrogels reduced their initial volume only three times under the same conditions. These results suggest that the phase transitions of the hydrogels may be used as quick predictors of the behavior of the polymer dispersions.

Keywords: Polyquaternium; SDS sorption isotherms; Microcalorimetry; Chemically cross-linked hydrogels

1. Introduction

Cationic polysaccharides (i.e. cationic celluloses, cationic guars, amino-modified starches, chitosan, and chitosan derivatives) are large-scale commercial products that have many useful characteristics such as hydrophilicity, biocompatibility, and antibacterial properties [1]. This group of polymers, just like anionic and non-ionic polysaccharides, can interact effectively with water, causing the medium to thicken. After drying, they can easily form biodegradable films and membranes with good mechanical properties. In addition, owing to their amino/ammonium groups, cationic polysaccharides show a natural attraction for some components of the skin and the hair [2]. This attraction increases the time that the dispersions remain on a biological

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* Corresponding author. Departamento de Farmacia y Tecnología Farmacéutica, Facultad de Farmacia, Universidad de Santiago de Compostela, 15782-Santiago de Compostela, Spain. Fax: +34-981-547148.

E-mail address: ffancon@usc.es (A. Concheiro).

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substrate, and if a drug were incorporated, the absorption process would be more efficient. This makes them particularly useful as bases for cosmetic preparations or topical drug delivery systems [1]. Additionally, the development of procedures to cross-link cationic polysaccharides has expanded their possibilities of application [3–5]. Polymer hydrogels that combine adequate mechanical properties with a high drug loading capability have shown an enormous potential as a basis for controlled drug delivery systems [6]. In the case of cationic cellulose hydrogels, the glucose backbone may establish hydrophobic or hydrogen bonding interactions, while the presence of cationically charged groups provides the system with a high affinity for oppositely charged molecules. Therefore, anionic amphiphilic compounds, such as NSAIDs or antidepressant drugs, seem to be optimum candidates to be formulated in these hydrogels [5]. To gain insight into the behavior of these systems, more information regarding the interaction process between cationic celluloses and surfactants, used as model molecules, is required.

Cationic polysaccharides and surfactants are commonly formulated together to improve their desired attributes (wetting, viscoelasticity, penetration enhancing) or to avoid unwanted problems affecting both the formulation process and stability [7]. Cationic cellulose/sodium dodecylsulfate (SDS) interactions in aqueous medium have been studied by a number of experimental techniques, including viscosity, surface tension, conductivity, dialysis or fluorescence [8–14]. Most of these polymers come from chemical modification, with cationically charged substances, of the hydroxyethyl substituents of hydroxyethylcellulose (HEC). Despite the fact that HEC interacts only very weakly with SDS, when there is a minimum of 0.05 quaternary ammonium residues per anhydroglucose unit, the absorption of SDS onto the polymer becomes possible [15]. Rheological data and phase diagrams [9,16] show that, in general, the relative proportions of the polymer and the surfactant govern the practical repercussions of their interactions. The surfactant begins to bind to the polymer at a critical aggregation concentration, *cac*, forming micelle-like aggregates along the polymer. Between the *cac* and the *cmc*, the surfactant favors the interpolymeric interactions, which result in the formation of a structured three-dimensional network, except when the surfactant and the polymer interact electrostatically, which results in the precipitation of the system at the neutralization concentration. Above the *cmc*, the surfactant will form micelles that can dissolve the complexes [11].

In shampoo, the cationic polymer is solubilized in high concentration solutions of anionic surfactants. Its dilution with water in a rising cycle, brings the polymer–surfactant composition into the complex-precipitation region, thus developing a hair-conditioning action [14]. The formation of complexes that behave as high surface activity compounds also has important repercussions on the foamability and foam stability [17]. In drug formulation, cationic polysaccharide–SDS complexes may greatly improve the capability of the polymer to solubilize hydrophobic drugs [18].

Kästner et al. [19] and Hoffman et al. [20] compared the behavior of HEC with cationic and hydrophobic groups in random distribution, or both cationic and hydrophobic groups at the same substituent. They observed that hydrophobic and cationic groups interact synergistically with the surfactant resulting in stronger viscoelastic systems, except in the precipitation region. Recently, Chronakis and Alexandridis [16] reported the influence of the molecular weight of the cationic cellulose on the elastic modulus and viscosity of the gels formed after addition of SDS at proportions below the neutralization of polymer charges.

While all such studies and techniques have provided valuable information about the nature of the interaction, the thermodynamics of the process as well as the influence of the structure of the cationic substituent have not yet been fully established. It is clear that an approach involving several techniques is ultimately most likely to provide a complete picture. In addition to former commonly used techniques, in this paper two techniques, microcalorimetric titrations and adsorption/desorption SDS isotherms on hydrogels, still scarcely used to characterize polymer–surfactant interactions, are also applied. We have selected polyquaternium-10 (PQ-10) and polyquaternium-4 (PQ-4), two HEC that carry the ammonium groups bonded to the hydroxyethyl substituent or directly grafted to the cellulose backbone, respectively, to evaluate the influence of the position of the cationic substituent on the interaction with the surfactant. No references to PQ-4/SDS association have been found in the literature. Also, it may be interesting to know if the volume transitions are permanent or reversible when the hydrogel is removed from the surfactant solution and immersed in water; and if this information may be used as a quick predictor of the intensity of cationic celluloses–SDS interactions. The information obtained could provide a deeper insight into the potential of cationic celluloses for biomedical applications, given their reduced acute and chronic toxicity [21].

2. Materials and methods

2.1. Materials

Polyquaternium-4 (PQ-4) (Celquat® H-100, batch FGS 1014) and Polyquaternium-10 (PQ-10) (Celquat® SC-230M, batch GFS 1139) were provided by National Starch and Chemical Ltd., UK. Sodium dodecylsulfate (SDS), pyrene, and ethyleneglycol diglycidylether (EGDE, 50 vol.% in water) were from Sigma Aldrich Chemical Co, USA. Purified water by reverse osmosis (MilliQ®, Millipore Spain) with resistivity > 1.82 milliΩ·cm was used. All other reactives were of analytical grade.

2.2. Methods

2.2.1. Preparation of the dispersions

Aqueous dispersions containing 0.50% (w/w) cationic cellulose and a wide range of SDS concentrations (0.005–0.50% w/w) were prepared by dispersing the required amounts of each component in 100 ml of water under stirring. The systems were left to stand for 24 h before characterization. All studies were carried out at 25 °C.

2.2.2. Surface tension

Surface tension measurements were made using the platinum ring method with a Lauda Tensiometer TD1 (Lauda-Königshofen, Germany) applying the necessary density corrections.

2.2.3. Steady-state fluorescence measurements

Pyrene emission spectra ($\lambda = 350-450$ nm) were recorded in a Perkin-Elmer LS50B fluorescence spectrophotometer (Buckinghamshire, England), with the excitation wavelength set at 310 nm and slits set at 5 for excitation and emission. The samples were prepared by addition of the polymer and the surfactant into a previously saturated and filtered pyrene solution (10^{-6} M), and stored at 20 °C for 24 h. The ratio of the intensity at the first (I_1 at 373 nm) and the third (I_3 at 393 nm) vibronic peaks was used as an index of the local hydrophobicity of the polymer/surfactant aggregates [22].

2.2.4. Titration microcalorimetry

Calorimetric experiments were performed in duplicate using a Tronac-450 isoperibol microcalorimeter and Tronac FS101 calorimetry software (Tronac Inc., Orem, UT), as described previously [23]. Briefly, in each experiment, a 47.5-ml cationic cellulose (0.5%) dispersion in water or in 0.9% NaCl medium was placed in a dewar reaction vessel, and a relatively concentrated surfactant solution (10%), in water or in 0.9% NaCl medium, was loaded into a 2-ml calibrated burette. The entire assembly was then immersed into a constant temperature water bath (25 °C). After thermal equilibration, the surfactant solution was delivered at a constant rate of 0.3332 ml/min into the reaction vessel, in which a stirrer mixed the two solutions rapidly. The rise or decrease in the temperature of the system was monitored using a thermistor, and later reproduced using a heating coil in the reaction vessel. The apparent enthalpy was calculated from the current and voltage applied and the heating time. As a blank, ultrapure water was used instead of cationic polymer dispersion. The enthalpy of the cationic polymer dilution (final concentration was 3% lower) was negligible. The enthalpy of micellization (ΔH_{mic}) and of aggregation (ΔH_{agg}) were estimated directly, from the plots of the recorded enthalpy vs. surfactant concentration, at the *cmc* and *cac*, respectively [24], and the enthalpy associated to the polymer/surfactant interaction (ΔHi) was estimated from

$$\Delta Hi = \Delta H_{\mathrm{agg}} - \Delta H_{\mathrm{mic}} \tag{1}$$

Similarly, ΔG_{mic}, ΔG_{agg}, and ΔGi were calculated using the following expressions [25,26]:

$$\Delta G_{\mathrm{mic}} = 2RT\ln(cmc) \tag{2}$$

$$\Delta G_{\mathrm{agg}} = 2RT\ln(cac) \tag{3}$$

$$\Delta Gi = \Delta G_{\mathrm{agg}} - \Delta G_{\mathrm{mic}} \tag{4}$$

Values of the entropy, ΔS_{mic}, ΔS_{agg}, and ΔSi were then derived from the appropriate values of ΔH and ΔG.

Additionally, from the integral heats of reaction at different times (Q_{i}, i.e. the difference between the heat evolved in the presence and absence of cationic polymer), the apparent binding equilibrium constant (K_{i}) and the Gibbs energy changes (ΔGi) per mol surfactant adsorbed were estimated, using FS101 software, by iterative convergence applying the least squares technique [27].

$$\Delta Gi = -RT\ln Ki \tag{5}$$

2.2.5. Rheological characterization of cationic polymer/SDS concentrated dispersions

Dispersions of 1% cationic cellulose with 0.05–1.0% SDS were prepared in a similar way to the diluted ones. The cloudiness of each system was determined in triplicate by measuring transmittance (800 nm, Shimadzu UV-240, Kyoto, Japan) at room temperature against a blank of 1.0% cationic cellulose dispersion. The rheological behavior was evaluated in triplicate at 25 °C in a Rheolyst AR-1000N rheometer (TA Instruments, Newcastle, UK) equipped with an AR2500 data analyzer, fitted with a Peltier temperature control, and a 4-cm-flat plate measuring geometry, or with a thermostatic concentric-cylinder adapter and a medium coaxial cylinder-recessed end. Oswald's equation:

$$\eta = m\dot{\gamma}^{n-1} \tag{6}$$

where η represents the viscosity, $\dot{\gamma}$ the shear rate, m the consistency index and n the fluidity index, was fitted to the flow curves. Oscillatory shear responses (G′ or elastic modulus, and G″ or viscous modulus) were determined at 0.1 Pa over the frequency range 0.05–50 rad·s^{-1}. The linearity of viscoelastic properties was verified for all the dispersions investigated.

2.2.6. Hydrogel synthesis

EGDE (2 ml) was added to a 3% cationic cellulose dispersion (10 ml) in 0.10 M NaOH medium [5]. After stirring for 5 min, the mixture was transferred to a test tube of 10.5 mm i.d., and hermetically closed. The tubes were kept at 60 °C for 24 h. After cooling, the hydrogels were carefully removed and immersed in ultrapure water for 24 h to swell. The hydrogels were then transferred to HCl 0.01 N solution for 12 h to neutralize the basic medium, and finally immersed in ultrapure water for 1 week, changing the medium every 12 h to allow a complete wash out of non-reacted substances.

2.2.7. SDS binding isotherm

Cylindrical pieces of each gel (3–4 mm thickness) were placed in glass vials containing 10 ml SDS solutions of different concentrations. The systems were closed and allowed to equilibrate for 3 days. After this time, SDS concentration in the solution surrounding the hydrogel was quantified using the Epton method, modified as follows [28,29]. A methylene blue hydrochloride stock solution was prepared by dissolving 0.1 g in 100 ml of water. To 15 ml of this solution, 25 g Na_2SO_4 and 3.4 ml H_2SO_4 were added and diluted with water up to 500 ml (MB solution). A 0.10-ml sample was pipetted into a 25-ml measuring cylinder with a screw cap and 8 ml water, 5 ml MB solution, and 9 ml chloroform were added. The cylinder was shaken by hand and then inserted in a rotary mixer for 10 min. The two phases were left to separate for 15 min. Then, SDS concentration was quantified measuring the absorbance of SDS-MB complex in the chloroform phase at 653 nm.

2.2.8. Hydrogel degree of swelling

Equilibrium diameters d of the cylindrical gels were measured using a digital micrometer. The degree of swelling was expressed as:

$$\text{Swelling ratio}: \; V/V_0 = (d/d_0)^3 \qquad (7)$$

where d_0 is the gel diameter upon synthesis.

3. Results and discussion

3.1. Cationic cellulose–SDS interaction in dilute solutions

Cationic hydroxyethylcellulose properties depend strongly on both the nature and extent of substitution. The polyquaternium-4 (PQ-4) and polyquaternium-10 (PQ-10) used in this study were previously characterized in detail [30]. PQ-4 has more hydroxyethyl groups and fewer ammonium groups than PQ-10 (Table 1).

Fig. 1 illustrates the phase diagrams for cationic cellulose (0.50%)–SDS–water systems. The two phase region is delineated by two boundaries, one at low surfactant concentrations, referred to as the coacervation line, and the other at high surfactant concentrations, referred to as the resolubilization line [10,18]. It can be seen that even 0.35% SDS was not enough to resolubilize 0.5% PQ-10/SDS precipitates. The surface tension (Fig. 2) of the dispersions in which the precipitation occurred were measured in the supernatant phase. In the cationic cellulose–SDS dispersions, the surface tension for low SDS proportions decreased faster than in SDS solutions. Then, a sudden increase is observed and a maximum in surface tension occurred (at 0.05% SDS). After a plateau region, the presence of more SDS caused the surface tension to reach the values observed for the surfactant only solutions. The maximum in surface tension is related to the *cac* [31], while the value at which the plateau region ends and converges on SDS solution values may be considered the saturation concentration (sc). Considering the number of ammonium groups in each polymer, the *cac* for PQ-4 and PQ-10 correspond to 2.61 and 4.02 ratios of ammonium to sulfate groups, respectively; while in the sc these ratios decreased to 0.52 and 0.80, respectively. Therefore, the surfactant begins to absorb onto the polymer at a concentration well below the neutralization level of polymer charges, and the process ends at a surfactant concentration greater than the neutralization point. These observations suggest the concomitance of both electrostatic and hydrophobic polymer–SDS interactions [15]. It is also interesting to note that the value of *cac* obtained with these cationic HEC (0.05% or 1.734 mM SDS) is much lower than the *cac* reported for non-ionic HEC (7.0 mM) [26] or other cellulose ethers, such as ethyl(hydroxyethyl) cellulose (3.0 mM) or hydroxypropyl methylcellulose (4.5 mM) [24], which demonstrates the important contribution of the ionic bonds to their affinity for the surfactant.

The micropolarity inside the surfactant-polymer aggregates was measured by the changes in the emission spectra of pyrene in the aqueous solution. Solubilization of pyrene in a hydrophobic environment was detected by a decrease in I_I/I_{III} ratio as a function of surfactant concentration [22]. Without surfactant, PQ-4 and PQ-10 dispersions had a I_I/I_{III} ratio around 1.15, while once the aggregates with the surfactant were formed, this ratio decreased to 0.95 in PQ-4 systems and to 0.75 in PQ-10 systems. The differences in the final I_I/I_{III} values indicate that PQ-10/SDS aggregates provide a more hydrophobic environment than PQ-4/SDS complexes. This may be related to the lower content in

Table 1
Molecular weight (MW), intrinsic viscosity in water ([η]), and characteristics of substitution of the cationic celluloses determined by ^{13}C-NMR [30]

Polymer	MW[a]	[η] (dl/g)	DS_2	DS_3	DS_6	DS_T	n	MS	%N
PQ-4	1,400,000	14.59	0.40	–	0.93	1.33	1.04	2.71	1.27
PQ-10	1,700,000	70.09	–	–	0.51	0.51	1.52	1.28	1.95

DS, degree of substitution; MS, molar substitution.

[a] Data provided by the supplier.

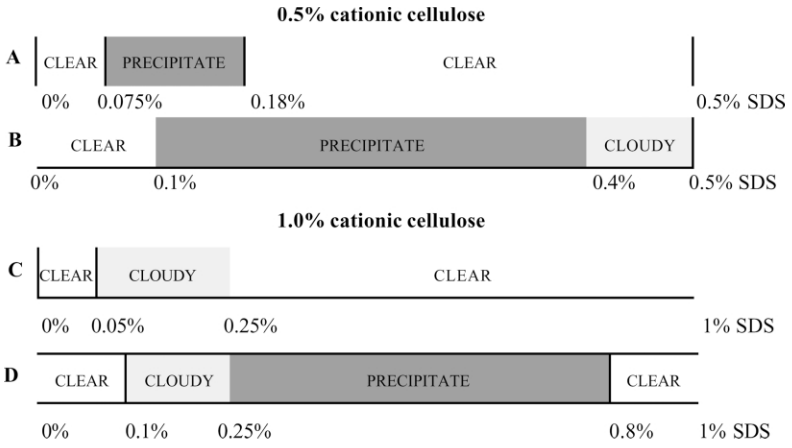

Fig. 1. Phase diagram for the PQ-4/SDS aqueous dispersions (A,C) and for the PQ-10/SDS aqueous dispersions (B,D).

hydrophilic hydroxyethyl groups of PQ-10 and to the stronger ionic interaction with SDS owing to a greater ammonium groups content, compared to PQ-4.

To obtain information about the thermodynamics of polymer–surfactant aggregation and surfactant micellization, microcalorimetric titration procedures are particularly useful [24,25,32]. Fig. 3 shows the apparent enthalpies associated to the demicellization, the interaction with cationic cellulose, and the micellization processes of SDS in 0.5% cationic cellulose dispersions compared to pure water. Before being added to the dewar containing water or cationic cellulose dispersion, SDS was above its *cmc* in the burette (10% w/w). Therefore, when the surfactant solution was slowly added to water, the micelles broke up until the concentration in the dewar reached *cmc*. In subsequent addition, micelles were only diluted in a solution of micelles. The SDS demicellization process was endothermic, while micelle dilution was slightly exothermic. The apparent enthalpy of micellization ($\Delta H_{\mathrm{mic}} = 2.3$ kJ/mol) and the transition concentration (5 mM) observed for SDS in pure water agrees well with the values obtained by Wang et al. [25].

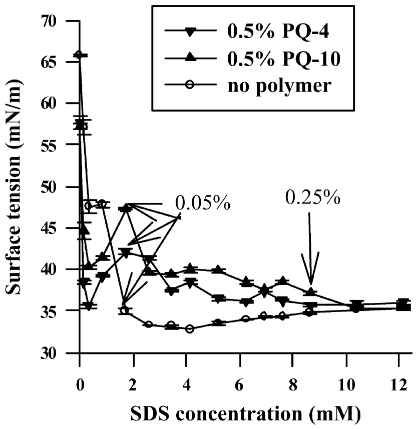

Fig. 2. Surface tension of SDS aqueous solutions in the absence and presence of 0.50% PQ-4 or PQ-10.

When the SDS solution was added to the cationic cellulose dispersions, the initial endothermic step almost disappeared, which indicates that as the micelles break up, the surfactant units interact electrostatically with the polymer, which is a strongly exothermic process. In the presence of PQ-4, the maximum binding enthalpy was reached around 2–4 mM SDS, although the process is exothermic in the whole range of surfactant analyzed. In contrast, in the case of PQ-10 a gradual increase in the heat evolved was observed, although the enthalpy associated to the interaction process was similar for both cationic celluloses (Table 2). The results shown in Fig. 3 and Table 2 indicate that for both PQ-4 and PQ-10, the interaction with SDS is enthalpically-driven. It is also important to note that similar thermodynamic results were found when the cationic celluloses and the surfactant were dispersed in NaCl 0.9% aqueous solution instead of water. This indicates that this high salt concentration, isosmotic with most

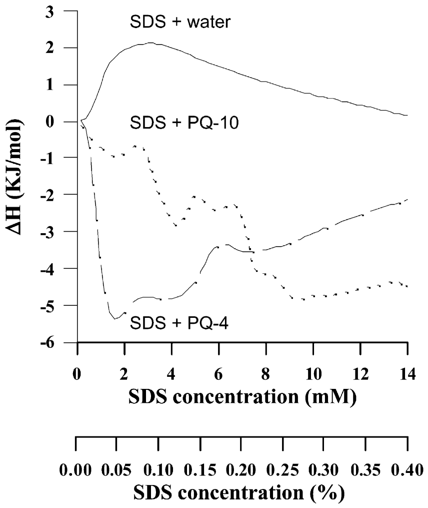

Fig. 3. Calorimetric titration curves observed during the addition of small volumes of 10% SDS solution into a dewar containing 0.5% PQ-4 or PQ-10 dispersion. The corresponding dilution plot of SDS in water is also given.

Table 2
Thermodynamic parameters for SDS-cationic celluloses aggregation in water

Polymer	ΔH_{agg} (kJ/mol)	ΔHi (kJ/mol)	ΔG_{agg} (kJ/mol)	ΔG_i (kJ/mol)	K_i^a	ΔG_i^a (kJ/mol)	ΔS_{agg} (J/molK)	ΔS_i (J/molK)
PQ-4	-5.5	-7.8	-31.5	-7.6	12.02	-6.2	$+87.2$	-0.8
PQ-10	-5.0	-7.3	-31.5	-7.6	17.38	-7.1	$+88.9$	$+0.9$

Standard deviations were in all cases lower than 5% (SDS: $\Delta H_{mic} = 2.3$ kJ/mol; $\Delta G_{mic} = -23.9$ kJ/mol; $\Delta S_{mic} = 88.0$ J/molK).

[a] Data obtained by iterative convergence from the integral heat of reaction at different times [27].

biological fluids, is not enough to break the strong ionic interaction.

This interaction behavior is clearly different from that previously reported for SDS interaction with non-ionic cellulose ethers including HEC, with which only hydrophobic bonds with the surfactant can be established and, in consequence, the process is endothermic but entropy-driven [25,26,32]. In our case, the interaction is much more intense and its repercussions on the stability and properties of the systems may be even more relevant.

3.2. Rheological behavior of 1% cationic cellulose–SDS systems

To evaluate the influence of SDS on the viscosity and elasticity of 1% cationic cellulose aqueous dispersions, a wide range of ammonium/sulfate group ratios was chosen. In PQ-4 dispersions, the range of SDS concentration in which the system became cloudy was again restricted to the neutralization region; while PQ-10 requires an important excess of SDS to resolubilize the aggregates (Fig. 1C,D). The systems became cloudy at concentrations similar to those observed for the dilute systems, while the SDS concentration required for resolubilization increased in proportion to the polymer concentration. The pH increased slightly from 7.0, without SDS, to 7.6 in the presence of 1% SDS.

Flow rheometry results showed that, in the absence of SDS, cationic cellulose dispersions behave as pseudoplastic fluids. Ostwald's equation fits the shear rate-shear stress plots well (correlation coefficients, r^2, >0.99). Fig. 4 shows the dependence of m (consistency index) and n (fluidity index) on the SDS concentration. In the absence of surfactant, the viscosity of PQ-10 dispersions was greater than that of PQ-4 systems, probably due to the greater molecular weight of the former. However, in the presence of SDS, the consistency of PQ-4 dispersions increased much more than that of PQ-10 systems, especially around the neutralization region.

PQ-10/SDS systems presented the highest consistency with the lowest (0.1%) and highest (1%) SDS concentrations evaluated. The systems in which precipitation occurs showed shear-thickening behavior ($n > 1$), which is characteristic of suspensions [33].

The dispersions were also analyzed using oscillatory rheometry. PQ-4 and PQ-10 only dispersions showed elastic modulus (G') lower than viscous modulus (G''), especially PQ-4. As observed previously in the flow rheometry experiments, the addition of SDS changed the viscoelastic behavior of the cationic cellulose dispersions dramatically (Fig. 5).

PQ-4/SDS systems had, for all SDS concentrations, higher G'' and much higher G' than the polymer solution. The maxima in G' and G'' (four orders of magnitude greater than PQ-4 only solutions) were observed to occur at 0.25–0.30% SDS, i.e. the concentrations in which the ammonium/sulfate groups ratio is close to 1. In this situation, G' and G'' were almost independent of the angular frequency, which is characteristic of well-structured entangled gels. This suggests that once established, the ionic bonds between the polar head of the surfactant and the ammonium groups of the polymer, the apolar tails of the surfactant act as bridges between the polymer chains. Above this surfactant concentration, additional surfactant molecules may form mixed micelles, breaking the interpolymeric bridges, and favoring intrapolymeric interactions. Thus the three-dimensional network disappears. For 0.70–1.0% SDS, G' was lower than G'' and dependent on the angular frequency applied.

PQ-10/SDS systems behaved very differently. For 0.05–0.10% SDS, G' and G'' increased up to two orders of magnitude with respect to the polymer only solution. In contrast, near the neutralization point, the precipitation of the system caused G'' to decrease brusquely, and G' to disappear. For 0.80–1.0% SDS, G' and G'' increased again. The rheological properties of PQ-10/SDS dispersions are similar to those previously reported for other cationic celluloses [9,16].

The opposite behavior of PQ-4 and PQ-10 systems may be attributed to their structural differences. PQ-4 has fewer ammonium groups, in small chains grafted to the cellulose backbone, and more hydroxyethyl substituents. Therefore, although the neutralization of charges causes the formation of a neutral polyampholyte, the presence of the free hydroxyethyl groups provides enough hydrophilicity to avoid the precipitation of the aggregates and contributes to the establishment of the three-dimensional network. In contrast, in PQ-10, the ammonium groups are directly bonded to the hydroxyethyl substituents, and in the aggregation process they may be included in the polyampholyte

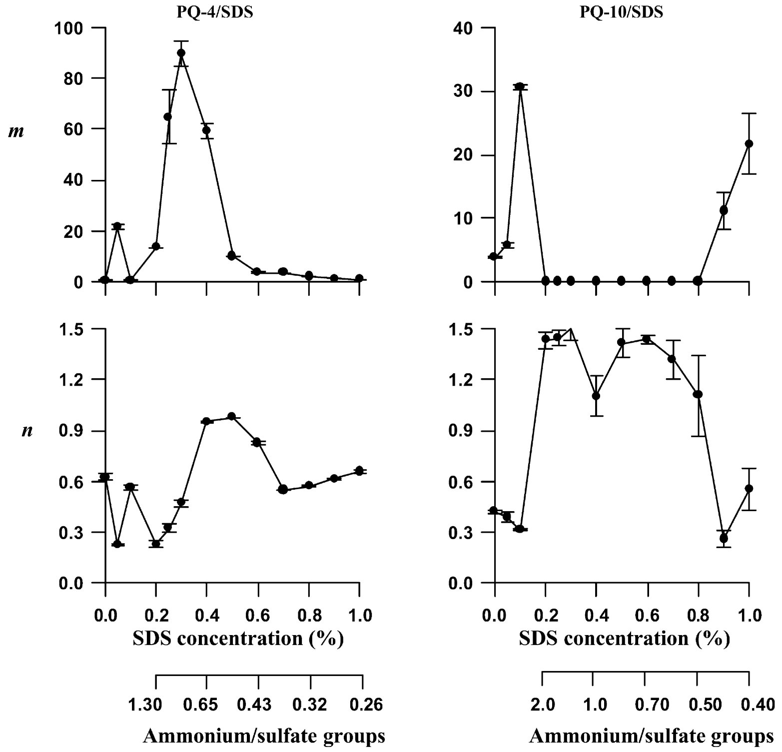

Fig. 4. Dependence of the consistency index (*m*) and the fluidity index (*n*) of dispersions of 1% PQ-4 or PQ-10 and SDS on the ammonium/sulfate groups ratio.

complex, contributing to the precipitation. Above 0.9% SDS, an excess of surfactant makes the complex have a global negative charge, swelling, and the free surfactant may form micelles able to solubilize the hydrophobic aggregates. This increases both G′ and G″. Fig. 6 is an attempt to explain the cationic cellulose/SDS binding process graphically.

3.3. SDS interactions with chemically cross-linked cationic cellulose hydrogels

The preparation of water super-absorbent hydrogels made of cationic cellulose has been described previously [5]. It was observed that these hydrogels may be used as biocompatible drug delivery devices because of their

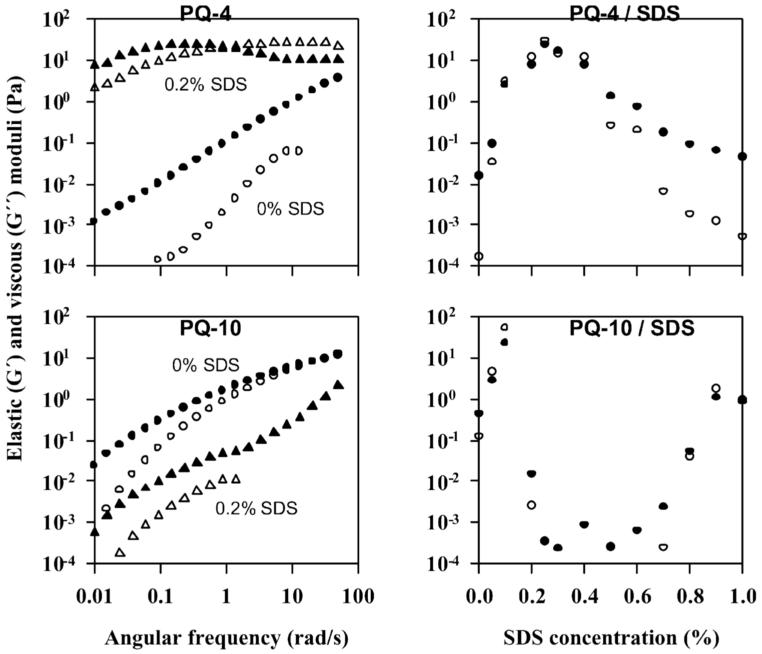

Fig. 5. Effect of SDS concentration on the elastic (open symbols) and viscous (full symbols) moduli of 1% PQ-4 or PQ-10 dispersion.

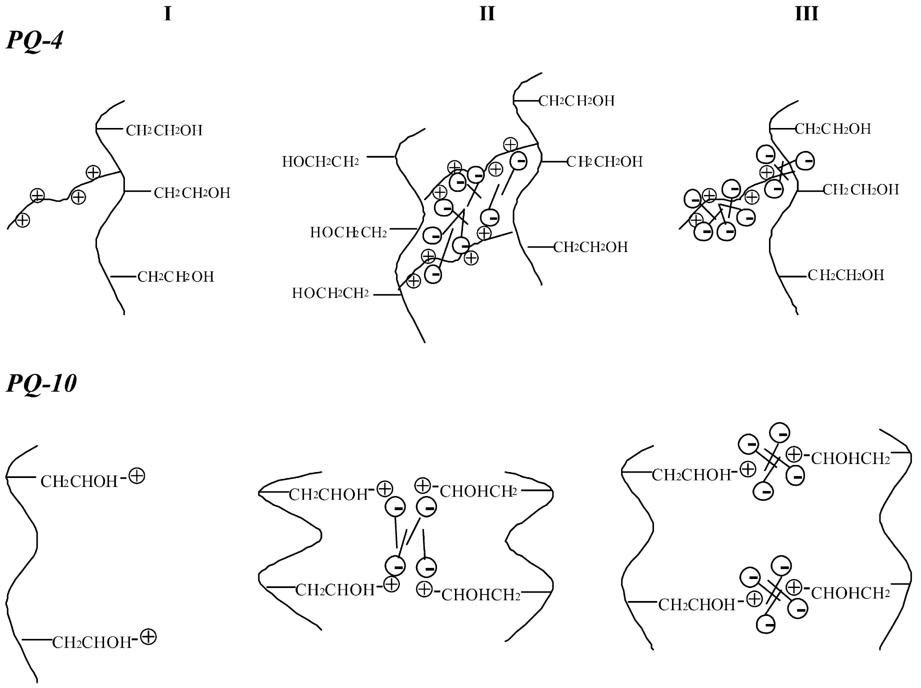

Fig. 6. Schematic drawing of the influence of the addition of SDS on the conformation of PQ-4 and PQ-10 chains in aqueous solutions when the ammonium/sulfate groups ratio is (I) higher than 1, (II) equal to 1, and (III) lower than 1.

adequate mechanical properties as well as their important water content, which may allow the diffusion of oxygen, nutrients, and drugs.

Hydrogel water content may be dramatically altered by the presence of interacting surfactants or other additives with surface activity, which may be the case of several drugs. Since cationic cellulose hydrogel preparation is relatively easy and, when it is immersed in SDS solutions, the changes in volume occurred relatively fast, volume transitions may be used as quick predictors of the interaction process. During surfactant absorption three simultaneous process may occur: (a) water flow from inside the hydrogel towards the surrounding solution, or vice versa, owing to differences in osmotic pressure; (b) surfactant diffusion towards the inside of the hydrogel due to a chemical gradient; and (c) polymer–surfactant binding [3,34].

PQ-10 hydrogels decreased their volume up to 20 times when the amount of SDS absorbed was around the neutralization of the ammonium groups of the polymer (Fig. 7). In the case of PQ-4, the hydrogels reduced only to 1/3 their initial volume under the same conditions. Above the neutralization point, when more SDS was absorbed, PQ-4 hydrogels swelled more than PQ-10 hydrogels, even though the SDS/ammonium groups mol ratio was similar for both systems (Fig. 7). These differences may be attributed again to the presence of free hydroxyethyl substituents (hydrophilic) in the PQ-4 structure. For the more concentrated SDS solutions, a plateau in absorption was observed, which suggests that the saturation binding corresponds to approximately 3.5 mol SDS per mol ammonium group in the

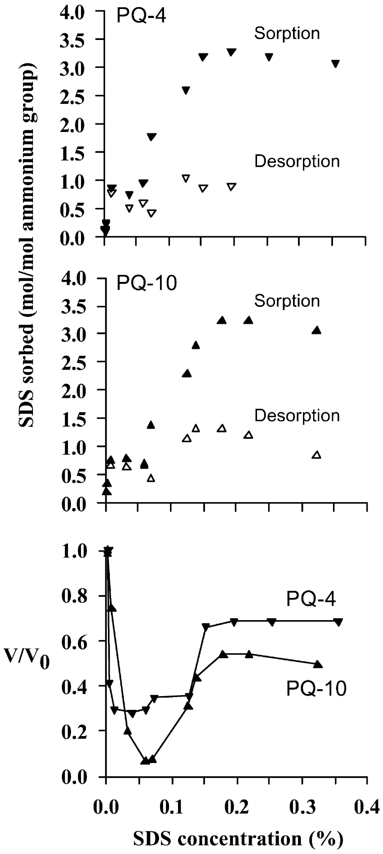

Fig. 7. Binding isotherms of SDS on cationic cellulose hydrogels and degree of swelling of the hydrogels at equilibrium.

hydrogel. This value is similar to that obtained for the absorption of SDS by other cationic celluloses using a dialysis membrane [15]. Therefore, two steps may be distinguished in the SDS isotherm. In the initial step, the electrostatic interaction is dominant, and the binding ratio corresponds to a 1 mol SDS/mol ammonium groups. The neutralization of the charges decreases the internal osmotic pressure inside the hydrogel, which shrinks. In the second step, a multi-molecular binding of SDS indicates that the interaction in this region is mainly hydrophobic. The saturation region occurs at a SDS concentration close to the *cmc*, independent of the structure of the cationic cellulose.

The release of the SDS absorbed was also quantified by immersion of the hydrogels in water. Fig. 7 shows that, when equilibrium is reached, the hydrogels contain approximately the amount of SDS needed to neutralize the ammonium groups. This indicates that, although the hydrophobic interactions disappeared when the system is diluted, the polymer–SDS ionic interactions are too strong to be broken. It is somehow surprising that the volume of the hydrogel remained practically the same as that observed in the SDS solutions, which indicates the continuance of the conformational state of the hydrogel caused by the initial absorption of SDS.

In summary, the high affinity of cationic cellulose for anionic amphiphilic molecules, as is the case of many drugs, and their two-step release process from the hydrogels (as first the hydrophobic and then the ionic interactions are broken), indicates that these systems may have a potential as drug delivery systems with a high loading capacity and able to regulate the drug release rate in specific environments depending on the dissociation rate of the complex.

4. Conclusions

Cationic cellulose–SDS interaction is an enthalpically-driven process in which ionic complex formation and hydrophobic bonding occur. Although surfactant binding isotherms were very similar for both polymers (saturation occurs at 3.5 mol SDS per mol ammonium groups), the relative distribution of the ammonium groups in the hydroxyethyl cellulose structure determines the practical repercussions of the interaction process. If the ammonium groups are directly grafted to the cellulose backbone, the free hydroxyethyl substituents make the complex have a hydrophilic character even when the ammonium groups are neutralized by the surfactant. In this situation, a three-dimensional network with particularly high elastic and viscous moduli is created. In contrast, if the ammonium groups are bonded to the hydroxyethyl substituents, these substituents may be included in the complex with the surfactant, exposing the less hydrophilic cellulose backbone to the aqueous medium. In consequence, the complex tends to precipitate and requires an important excess of surfactant to be resolubilized. This different behavior was easily seen also in the surfactant-induced shrinking of the hydrogels around the charges neutralization, which suggests that the volume transitions of the hydrogels may be used as quick predictors of the surfactant-polymer compatibility in an aqueous medium.

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