Colloids and Surfaces A 524 (2017) 185–192

Contents lists available at ScienceDirect

Colloids and Surfaces A

journal homepage: www.elsevier.com/locate/colsurfa

Investigation of the elastic and adhesion properties of adsorbed hydrophobically modified inulin films on latex particles using Atomic Force Microscopy (AFM)

M. Obiols-Rabasa[a,b,1], G. Oncins[c], F. Sanz[b,d,e], Th.F. Tadros[f], C. Solans[a,b], B. Levecke[g], K. Booten[h], J. Esquena[a,b,*]

[a] Institute of Advanced Chemistry of Catalonia, Consejo Superior de Investigaciones Científicas (IQAC-CSIC), Jordi Girona 18-26, 08034 Barcelona, Spain
[b] Member of CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Spain
[c] Scientific and Technological Centers of the University of Barcelona, Soler i Sabaris 1, 08028 Barcelona, Spain
[d] Nanoprobes and Nanoswitches, Institute for Bioengineering of Catalonia (IBEC), Baldiri Reixac 13, 08028 Barcelona, Spain
[e] Department of Physical Chemistry, Faculty of Chemistry, University of Barcelona, Martí i Franquès 1-11, 08028 Barcelona, Spain
[f] 89 Nash Grove Lane, Wokingham, Berkshire, RG40 4HE, UK
[g] Beneo Bio Based Chemicals, Remylaan 4, B-3018 Leuven-Wijgmaal, Belgium
[h] CreaChem, Tienen Business Centre, Leuvenselaan 172, 3300 Tienen, Belgium

ARTICLE INFO

Keywords:
Steric repulsion
Colloidal stability
AFM
Interaction forces

ABSTRACT

Graft polymer surfactants provide very good colloidal stability because of strong steric repulsions between adsorbed surfactant films. The elastic and adhesion properties of adsorbed hydrophobically modified inulin polymer surfactant (INUTEC NRA) have been directly measured using Atomic Force Microscopy (AFM) measurements. For this purpose, poly(methyl methacrylate/butyl acrylate), P(MMA/BuA), latexes prepared in the presence of the hydrophobically modified inulin (INUTEC NRA) were used. These latexes (diameter 118 nm and polydispersity index of 1.05) showed a very high colloidal stability in water and in the presence of electrolyte (up to 0.2 mol dm^{-3} KBr). The latexes were deposited on mica, which was silanated to enhance the adhesion of the latex particles to the surface. A silicon nitride tip with approximately 10 nm diameter that also contained an adsorbed layer of surfactant was used in the AFM apparatus. The tip was allowed to approach, contact thereafter the particles with an applied force of 12.5 nN, and finally detach from the film. Both elastic (Young's) modulus of the film and adhesion force were studied. The results showed that the adsorbed surfactant films are highly elastic and their elastic modulus and adhesion force did not change significantly with the presence of Na_2SO_4 up to 0.05 mol dm^{-3}. The high elastic contribution to the steric interaction ensures strong repulsion between the latex particles both in water and at high electrolyte concentrations. In addition, the lack of dependence of adhesion force on electrolyte concentration ensures uniform deposition of the latex particles on a flat substrate as for example in coating applications. These results show the advantages of using a graft polymer surfactant for enhancing the stability of particle suspensions, as illustrated in previous investigations.

1. Introduction

Biocompatible surfactants are added as excipients in compressed tablets for oral administration of insoluble drugs. Currently, tablets constitute the most common dosage form, and often, surfactants are required to increase the dissolution rates of drugs, improving its bioavailability [1]. Consequently, there is a great interest in biocompatible nonionic copolymer surfactants that can enhance colloidal stability. An interesting biocompatible surfactant can be synthesized by anchoring alkyl chains on inulin (polyfructose), producing a graft copolymer that consist of a polar main chain with hanging hydrophobic tails [2]. Recently, this surfactant (denoted as INUTEC NRA) has been studied as dissolution enhancer of drugs in tablet formulations, achieving fast disintegration of tablets [3–5]. Moreover, it has been shown that this surfactant is an appropriate carrier for hydrophobic drugs with poor water solubility, increasing the drug concentration in dispersions, and thus, enhancing the release and bioavailabity [6–9].

In a previous publication [10] we have reported the interaction

---

* Corresponding author at: Institute of Advanced Chemistry of Catalonia, Consejo Superior de Investigaciones Científicas (IQAC-CSIC), Jordi Girona 18-26, 08034 Barcelona, Spain.
E-mail address: jordi.esquena@iqac.csic.es (J. Esquena).

[1] Current address: CR Competence AB, Naturvetarvägen 14, 22362 Lund, Sweden.

http://dx.doi.org/10.1016/j.colsurfa.2017.04.048
Received 5 February 2017; Received in revised form 20 April 2017; Accepted 21 April 2017

forces between two layers of this biocompatible surfactant, adsorbed on a glass sphere and plate using Atomic Force Microscopy (AFM). The AFM results showed that in the presence of INUTEC NRA, at concentrations greater than $1.6 \cdot 10^{-4}$ mol dm^{-3} (corresponding to full coverage of the surfaces with surfactant), the force increased very rapidly with decrease of distance at separation distances below 18 nm. This was due to very strong repulsion occurring as a result of the steric interaction between the strongly hydrated loops and tails of inulin. The results revealed an INUTEC NRA layer thickness to be about 9 nm and that clearly showed the strong hydration of polyfructose backbone. Moreover, the effect of electrolyte, sodium sulfate, on the force-distance curve was also studied. It was found that the interaction remained repulsive even at high electrolyte concentrations, although the electrolyte reduced polymer layer thickness from approximately 10 nm at 0.3 mol dm^{-3} of electrolyte to 3 nm in the presence of 1.5 mol dm^{-3} of electrolyte.

This reduction in adsorbed layer thickness, as a function of Na_2SO_4 concentration, was attributed to a change in conformation of polyfructose chains because of their partial dehydration, since solubility of polyfructose gradually decreases with Na_2SO_4 concentration [10]. However, even at such low adsorbed layer thickness (3 nm), strong repulsive interaction was observed, indicating an intense steric repulsion. This was confirmed by observing neat repulsive forces on approach, even at high electrolyte concentration. This clearly indicated that the surfactant is an effective colloidal stabilizer by steric repulsion, as already observed in the stabilization of clay particles [11], suspensions of various nanocrystals [12,13], and carbon nanotubes [14]. Moreover, the adsorption isotherm of INUTEC NRA surfactant on rubber latex particles showed a saturation concentration of 3.38×10^{-7} mol m^{-2} with a high adsorption constant of 1.57×10^{7} [15].

In addition, other studies on the use of INUTEC NRA in other systems, i.e. emulsion films, revealed that such surfactant formed stable Newton Black Films (NBF) which resists rupture up to a disjoining pressure of 45 kPa even in the presence of electrolytes [16]. The above studies demonstrated that INUTEC NRA surfactant layers can provide excellent stabilization of colloidal dispersions due to strong steric repulsions.

These results could not explain the origin of these repulsions and the reason for the high stability in the presence of electrolytes, in terms, for instance, of elastic and adhesion properties when the surfactant layers absorbed onto particles and begin to interpenetrate and/or compress. Such information is very important for understanding the colloidal stability of particle dispersions and the rapid dissolution rate in compressed tablet formulations.

In the present paper, a more realistic approach for the determination of the interaction between two INUTEC NRA surfactant layers is carried out. Thus, latex particles containing the adsorbed surfactant were deposited on a flat surface and the elastic and adhesion properties with another surfactant layer that is adsorbed onto the silicon nitride tip of the AFM instrument were measured. For this purpose, poly (methyl methacrylate/butyl acrylate) latexes, P(MMA/BuA), were prepared using emulsion polymerization in the presence of INUTEC NRA surfactant and these latexes were characterized by dynamic light scattering (DLS) and transmission electron microscopy (TEM). The latexes were deposited on a mica surface, which was modified to enhance the latex adhesion, by surface functionalization with amminopropyl triethoxysilane (APTES). The elastic and adhesion properties of the adsorbed layers of surfactant could be obtained by application of a force after the layers begin to touch.

2. Experimental

2.1. Materials

Two main monomers were used, methyl methacrylate and butyl acrylate, both from Quimidroga. As co-monomers, acrylic acid (AA) and methacrylic acid (MAA), both supplied by Fluka, were employed. Silicon nitride powder, S_3N_4, ($\geq$99.9%) was purchased from Sigma. 3-Aminopropyl triethoxysilane, $H_2N(CH_2)_3Si(OC_2H_5)_3$ (APTES), was also provided by Sigma ($\geq$99%). Water was always MilliQ purified and filtered, and experiments were performed as a function of Na_2SO_4 concentration (Na_2SO_4 anhydrous, $\geq$99%, from Merck).

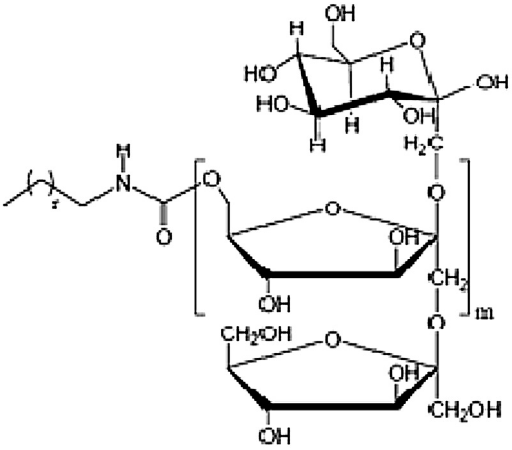

Fig. 1. Structure of the inulin-derivative surfactant (Adapted from ref. 2, with permission of American Chemical Society).

INUTEC NRA is a graft copolymer consisting of inulin (linear polyfructose) with degree of polymerization greater than 23 on which several C12 alkyl chains are randomly grafted on the backbone [2], as depicted in Fig. 1. This molecule has an average molecular weight of 5040 g mol^{-1} and it was supplied by Beneo Bio Based Chemicals (Belgium).

2.2. Latex preparation

Details of P(MMA/BuA) latex preparation was described in detail earlier by Obiols-Rabasa et al. [17] Basically, two monomers (methyl methacrylate and butyl acrylate) were used to prepare the latex in the presence of hydrophobically modified inulin surfactant (INUTEC NRA).

A seed was first prepared in a batch reactor using sodium lauryl sulfate (SLS). The volume average diameter of the seed was 43 nm (with polydispersity index of 1.05) as obtained by TEM. To this seed water, buffer, initiator and surfactant were added and the polymerization was carried out in semicontinuous process by feeding MMA and BuA monomers at 80 °C. The latex obtained was 37 wt% solid content and the volume average diameter of the particles was 118 nm as determined by TEM with a polydispersity index of 1.05 (indicating near monodisperse particles). The particle size was also determined by DLS, with an average diameter of approximately 139 nm.

2.3. AFM measurements

A Multimode AFM attached to a Nanoscope IV electronic controller (Veeco Digital Instruments, USA, currently Bruker) was used for this purpose. An exfoliated mica sheet was attached to a Teflon disc that was previously cleaned in piranha solution for 30 min so as to remove any contamination. Afterwards, the Teflon disc was thoroughly rinsed with ethanol, acetone and milliQ water. The Teflon was glued on a metallic disc and then placed on the magnetic holder of the microscope. The mica was silanized by exposing its exfoliated surface to amminopropyl triethoxysilane (APTES) vapours for 2 min at room temperature. 30 μl of latex solution (0.05 wt%) were placed on the mica surface and left for 5 min. This gentle procedure was enough to anchor the particles on mica, obtaining partial coverage of mica surface with a monolayer of particles, as clearly observed in the AFM image (Fig. 2). A Si_2O_3 tip was