

Formulation of Biobased Polymers Films to Target Specific Surface Properties

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Cellulose derivatives are promising raw material as emulsifier, thickening or suspending agent, excipient, drug release agent, adhesive or water-based coating for food, building or pharmaceutical industries. Additives such as plasticizers or surfactants are frequently incorporated into such biopolymers to improve their properties. The aim of this work is to formulate, by introducing dedicated additives, biopolymer films based on cellulose derivatives and to explore their surface properties. The study investigates the influence of hydrophilic and hydrophobic additives on the surface properties of hypromellose films. The surface structure and morphology of hypromellose films shows the presence of nano-clusters, the which disappear as surfactant content increases. So does the surface average roughness and the surface free energy of the formulated films, suggesting the formation of a weak boundary layer at the film surface. As a consequence, a sharp decrease of nano-adhesion and nanofriction forces is observed. Hydrophilic additive induces the swelling of hypromellose clusters and an increase of the film surface free energy as well as nano-friction and nano-adhesion forces. The present study clearly underlines the strong dependence of the surface properties of the formulated films on additive nature and concentration as well as the interplay with additive-biopolymer matrix compatibility. Formulation appears then as an original and simple way to tune and target surface morphology and surface properties of biobased polymer films.

1. Introduction

Cellulose-based polymers are biodegradable and environmentally friendly. For this reason, they are dedicated for a number of industrial uses, especially in cases where environmental issues are concerned, as well as biomedical applications. Hypromellose is a polysaccharide biopolymer based on modified cellulose (cellulose ether) and available at different molecular weight that present great interest for food, pharmaceutical or building industries. The polymer bulk properties which derive from the polymer molecular properties are solubility, biocompatibility, biodegradability and stability. Bulk properties are based on key attributes like efficient thickening, surface activity and film-forming ability. Suppliers produce it with different properties and dissimilar purity due to broad source of cellulose in nature. Therefore, formulation appears as an important way to improve and target specific properties such as flexibility, water affinity, drying as well as surface properties like wettability, adhesion and friction. Cellulose ethers are the preferred materials in the formation of films and coatings for the biomedical and pharmaceutical industries or for adhesives in the building industries. Additives are then incorporated during the formulation process to improve bulk and surface properties. Among them plasticizers are used in films and coatings formulations to improve bulk properties and increase the flexibility and reduce the brittleness of the film. Surface-active agents (surfactants) are also widely used in films and coating formulations to improve wettability and control adhesion and lubrication of the films and coatings due to their adsorption at surfaces or interfaces, even at low concentrations. The main objective of this work is to formulate hypromellose films by introducing dedicated plasticizer or surfactant additives and to explore their impact on surface properties at molecular, nanoscopic and macroscopic scales.

2. Materials and techniques

2.1 Hypromellose

Hypromellose (HM) is a semi synthetic polymer obtained by chemical reaction of the hydroxyl groups at positions 2, 3 and/or 6 of the anhydroglucose residues of cellulose, which is made of D-glucopyranose units of conformation chair, bonded through $\beta(1\rightarrow4)$ glycosidic linkages. Hypromellose contains two types of substituents: the methoxy group (OCH_3) and the hydroxypropyl group ($\text{OC}_3\text{H}_6\text{OH}$). Hypromellose (HM) was kindly supplied by Colorcon (France). The chemical structure of hypromellose is reported in Figure 1.

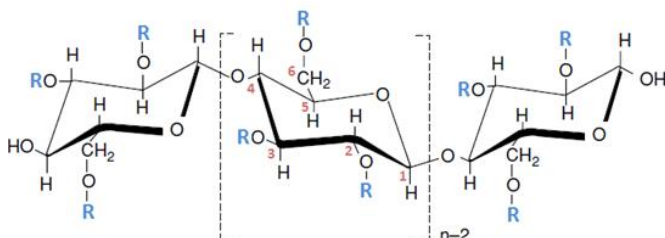


Figure 1: Chemical structure of hypromellose; $R = \text{H}, -\text{CH}_3$ or $-\text{OC}_3\text{H}_6\text{OH}$

Hypromellose properties are impacted by the methoxy group content and the hydroxypropyl group content. Quantification of these substitutions refers to the degree of substitution (DS) and to the molar substitution (MS). Each anhydroglucose unit in the cellulose chain has three hydroxyl groups available for substitution. Thus, if all three available positions on each unit are substituted, the DS value is equal to 3, if average of two on each anhydroglucose unit is substituted, the DS value is equal to 2. Moreover, the number of moles of hydroxypropyl group per mole of anhydroglucose unit in the chain is named MS. Along the cellulose chain, methyl substitutions constitute hydrophobic domain whereas hydroxypropyl substitutions constitute hydrophilic one. As a consequence, the highest the degree of substitution, the highest the polymer hydrophobicity and the interfacial activity (Camino et al., 2009). The Hypromellose grade used in this study has a nominal viscosity of 3 mPa.s at 2% aqueous solution at 20°C. The degree of substitution (DS) of methoxy groups and the molar substitution (MS) of hydroxypropyl groups are 1.87 and 0.25 respectively. By weight percent, the amount of OCH_3 groups is 28.3 % (w/w) and $\text{OC}_3\text{H}_6\text{OH}$ groups is 9.1% (w/w).

2.2 Additives

Stearic acid ($\text{C}_{18}\text{H}_{36}\text{O}_2$) and polyethylene glycol ($\text{C}_2\text{H}_4\text{O}$)_n were supplied by Sigma-Aldrich and are used as additives for film forming process without supplementary purification. Polyethylene glycol chains have average molecular weight ranging in between 380-420 $\text{g}\cdot\text{mol}^{-1}$ and are highly soluble in water. Polyethylene glycol density is equal to 1.128 $\text{g}\cdot\text{cm}^{-3}$. The purity of the additives is greater than 99 %. Polyethylene glycol is non-toxic and is widely used (Fuertges and Abuchowski, 1990) by biomedical, pharmaceutical, food and cosmetic industries as excipient, rheological and film-forming agent. Stearic acid is derived from edible fat and is widely used as surfactant and lubricant (Rowe et al., 2006).

2.3 Hypromellose film formation

Pure hypromellose films were obtained by preparing the HM solutions (6% w/v) and casting the solution onto a glass plate (Petri-dish), then drying it at ambient conditions. HM solution (6% w/v) was prepared by dispersing HM powder under moderate agitation in deionised water at 80-90°C. HM was dissolved by hydration and cooling to $25 \pm 2^\circ\text{C}$. A clear solution is obtained after cooling. To achieve the maximum hydration of HM polymer, solution was preserved at 5°C for 24h. To obtain 100 μm thick films, solutions were poured in uniform layer of 1.6 mm thickness onto a glass plate. Films were formed by drying under natural convection for 48h. The dried films were peeled from the glass plates and samples were conditioned at $25 \pm 2^\circ\text{C}$ and $30 \pm 5\%$ RH before experiments.

2.4 Formulation of HM-stearic acid films and HM-polyethylene glycol films

HM formulated films were prepared by incorporation of additives in HM solution. Additive content was expressed as weight percent of HM powder. For HM-stearic acid films, fatty acid was firstly dissolved in 10 ml of absolute ethanol, and then added to HM solution under magnetic agitation. Four different solutions with various stearic acid contents were prepared (0.05%, 0.1%, 0.5% and 1% w/w). The polyethylene glycol has been added to HM solution without solubilization in ethanol due to its high solubility in water. Four solutions were also prepared

(10%, 20%, 30% and 40% w/w). All solutions were then homogenized for 2h and preserved for 24 h at 5°C. Film-forming solutions were spread onto a glass plate to form uniform layers of 1.6 mm of thickness, and dried under natural conditions. In order to compare properties of the samples, all formulated films were preserved at 25 ± 2 °C and $30 \pm 5\%$ RH before experiments.

2.5 Differential Scanning Calorimetry (DSC)

DSC is a widely used method for thermal analysis. Thermal events that may be studied include melting, crystallization, glass transitions and decomposition reactions. Thermal analysis of samples was performed using a Mettler Toledo DSC822e calorimeter. The DSC scans were carried out under a nitrogen purge and the samples of mass in between 20-30 mg were placed in 100 μ l aluminium pans. An empty pan was used as reference. The samples were firstly cooled to -50 °C, held isothermally for 5 min and then heated to 180 °C to evaporate moisture. In order to determine the glass transition temperature, samples were cooled to -50°C, held isothermally for 5 min, then re-heated to 250 °C. A scanning rate of 10°C/min was set for all heating and cooling ramps.

2.6 Wettability – Contact angle measurements

Contact angles were measured by depositing a drop of a liquid onto the film surface. The drop is imaged and the resulting contact angle is determined by drop shape imaging. The instrument used is a Krüss G2 Goniometer. The contact angle measurements were carried out in open air at a relative humidity of $30 \pm 5\%$ RH and at a room temperature of 22 ± 2 °C by using three liquids: water, diiodomethane and α -bromonaphtalene. The volume of droplets is ranging in between 2-3 μ l. Ten droplets were imaged at different regions of the same piece of film. The contact angle is averaged over these ten values. The surface free energy of the films was determined from the experimental contact angles and surface tensions of the probe liquids. The Owens and Wendt (Owens and Wendt, 1969) approach was used to access both dispersive (γ_s^d) and non-dispersive (γ_s^{nd}) surface energies of the films according to $\gamma_l(1+\cos\theta) = 2(\gamma_s^d\gamma_l^d)^{1/2} + 2(\gamma_s^{nd}\gamma_l^{nd})^{1/2}$ where θ is the contact angle of the liquid droplet on the film solid surface, γ_l^d and γ_l^{nd} , are respectively the dispersive and non-dispersive components of the surface free energy of the liquid, and γ_l is the surface free energy of the liquid.

2.7 Atomic force microscopy (AFM)

AFM experiments were carried out using a Nanoscope IIIa controller from Digital Instruments (USA) in both tapping and contact modes in order to access surface topography, hydrophilic/hydrophobic character of the surface as well as adhesive and friction properties at the nanoscale. Topographic measurements of HM and HM formulated films are realized by using the tapping mode. Topographic measurements are made at fixed scanning angle equal to 0°. AFM silicon probes (Veeco) have a spring constant of 5 N.m⁻¹, a resonance frequency of 150 kHz and a tip radius < 10 nm. All images were collected with a resolution of 512 x 512 pixels and a scan rate of 0.8 Hz for 1 μ m x 1 μ m images. All experiments were performed in air at ambient conditions. The measurement of adhesion force between the AFM tip and HM and HM formulated films was performed in contact mode by recording force-distance curves. At jump-out of contact of the tip from the film surface the adhesion force is equal to $F = k \cdot \Delta z$, where k is the cantilever spring constant (N/m) and Δz is the cantilever deflection (nm). Silicon nitride Si₃N₄ cantilevers of 115 μ m length, 57 kHz resonance frequency with pyramidal sharpened tips were used. The spring constant was equal to 0.3 N.m⁻¹ and the radius of curvature of the tip was equal to 45 nm. Friction forces were also measured by AFM. Under a given applied load (F_N), the sample is scanned back and forth in a direction perpendicular to the long axis of the cantilever and the output of the horizontal two quadrants of the photodiode detector is measured. The friction force between the film and the tip produces a twisting of the cantilever. The differential signal between the left and right quadrants of the photodiode detector can be related to the degree of twisting, hence to the magnitude of friction force. Nanoscale friction is quantified by TMR (Trace Minus Retrace, in volts, equal to the difference between lateral forces scanning left-to-right and right-to-left. This signal can also be influenced by adhesive force (F_{ADH} at the tip-sample interface.). In this case, to calculate friction coefficient (μ), friction force (F_{TMR}) should be divided by the sum of applied load (F_N) and adhesion force (F_{ADH}). In the presence of capillary force, the coefficient of friction is given (Bushan, 2005) by $\mu = F_{TMR} / (F_N + F_{ADH})$.

3. Results and discussions

3.1 Thermal properties of HM and HM formulated films

Thermal analysis is used to investigate chemical and physical transitions of HM and HM formulated films as a function of temperature. DSC analysis of pure HM film indicates a glass transition temperature (T_g) equal to 138°C. No peak corresponding to the melting of a crystalline phase is observed. HM formulated films containing

0.05%, 0.1%, 0.5% and 1% (w/w) of stearic acid (SA) molecules showed no variation of the glass transition temperature which remains unchanged relative to pure HM and equal to 138°C. The melting temperature of SA remains also unchanged in formulated films. These results indicate that phase separation occurs between the Hypromellose that behaves as a hydrophilic matrix and stearic acid that behaves as a hydrophobic additive. Phase separation could be explained by the absence of HM-SA interactions. On the contrary DSC thermograms of HM-Polyethylene glycol (HM-PEG) films exhibit only one glass transition temperature (T_g) which value ranges between the glass transitions of the two constituents, HM and PEG. In addition, the fact that both constituents are water soluble promotes miscibility between them and prevents phase separation. HM pure film is in the amorphous state and presents a glass transition temperature equal to 138°C. However, addition of PEG which has a T_g equal to -72°C changes the thermal properties of HM formulated films. Indeed, increasing PEG content in formulated films induce, first, a unique T_g for the blend and, second, a decrease of the glass transition temperature as reported in Table 1.

Table 1: Glass transition temperature of HM and HM-PEG films versus PEG content

	HM	HM-10% PEG	HM-20% PEG	HM- 30% PEG
T _g (°C)	138	98	70	50

A unique T_g means that HM-PEG blends are miscible due to strong interactions between the two polymers. One can conclude that PEG affects thermal properties of HPMC films. Literature studies (Kondo et al., 1994) have established that the primary hydroxyl groups on cellulose and methylcellulose form predominantly hydrogen bonds with the ether oxygen of PEG. This opens the possibility of interactions between the hydroxyl groups of HM and PEG supporting the fact that HM-PEG blends are miscible.

3.2 Water contact angles of HM and HM formulated films

Evolution of the surface hydrophobic character of HM formulated films with incorporation of stearic acid (SA) and polyethylene glycol (PEG) was investigated by water contact angle measurements. As mentioned above, the contact angle is defined as the angle between the substrate surface and the tangent line at the point of contact of the liquid droplet with the substrate. Table 2 shows the contact angle values of water droplets on HM, HM-PEG films for 40%, 30%, 20% and 10% (w/w) polyethylene glycol (PEG) content and HM-SA films for 0.05%, 0.1%, 0.5% and 1% (w/w) stearic acid (SA) content.

Table 2: Water contact angles values on HM, HM-PEG and HM-SA films

HM	40% PEG	30% PEG	20% PEG	10% PEG	0.05% SA	0.1% SA	0.5% SA	1% SA
69° ± 2°	21 ± 2°	22 ± 2°	43 ± 2°	57 ± 2°	76° ± 2°	84° ± 2°	91 ± 2°	94 ± 2°

From Table 2 it is possible to conclude that the water contact angle decreases with introduction of PEG (from 69° for pure HM film to 21° for HM + 40% w/w PEG films), indicating an increase of the hydrophilicity of the film surface. Also, the addition of stearic acid increases the water contact angle value of HM-SA formulated films from 76° to 94°, indicating an increase of the hydrophobicity of the film surface. Thus formulation of HM with dedicated amount of PEG or SA allows to tune the hydrophilic/hydrophobic character of the film surface, from highly hydrophilic (contact angle = 21°) to highly hydrophobic (contact angle=94°). In terms of surface energies, the initial surface free energy of pure HM film is 43 mJ.m⁻², as determined from wettability measurements. This surface energy has two components: a dispersive one (33 mJ.m⁻²) and a non-dispersive (polar) one (10 mJ.m⁻²). Addition of stearic acid (even for low content i.e. 0.1% (w/w) SA), induce a strong decrease of surface free energy that reach a value of 31.3 mJ.m⁻² for 1% (w/w) SA. This decrease is mainly due to the strong decrease of the non-dispersive (polar) component of the surface energy. Thus the hypothesis of surface migration of SA chains to the top film surface, promoted by phase separation, is highly probable. The addition of a hydrophilic additive such as PEG (surface energy of PEG = 48 mJ.m⁻²) increases logically the surface energy of the HM-PEG formulated films. Incorporation of PEG affects both components of the surface energy. The polar component triplicates by addition of 30% of PEG (30 mJ.m⁻²). Moreover, the surface energy reaches values

closed to 73 mJ.m^{-2} (equal to the surface tension of water = 72.8 mJ.m^{-2}). The addition PEG generates higher adsorption of water molecules in HM formulated films. In addition, the presence of PEG molecules between the HM chains increases the free volume in the polymer network. This fact constitutes also an additional factor that contributes to keep the water molecules trapped within the film. Thus, the increase of hydrophilic surface properties of HPMC-PEG films, might be explained by bonded H_2O molecules on film surface (Lepifre et al., 2004). To conclude, addition of PEG chains induces an increase of the hydrophilic character of HM-PEG formulated films.

3.3 Surface topography of HM and HM formulated films

The surface topography of HM and HM formulated films was carried out by using tapping-mode atomic force microscopy. Figure 3 shows the surface topographic images ($1 \mu\text{m} \times 1 \mu\text{m}$) of HM and HM formulated films. They show the presence of nano-domains, usually called clusters in the literature, with a characteristic size. HM nano-domains are due to aggregates of HM chains in the film-forming solution. For pure HM film, the average clusters size is 20-30 nm. The hydrophobic interactions between the hydrophobic substituents of HM polymer chains induce the formation of these aggregates or clusters (Camino et al., 2009).

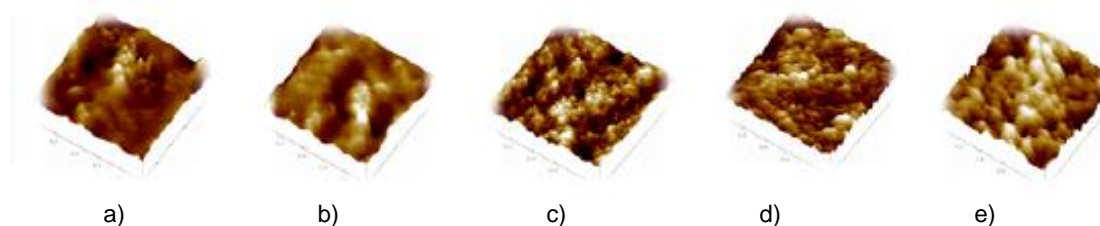


Figure 3: Tapping-mode AFM topographic images ($1 \mu\text{m} \times 1 \mu\text{m}$) of HM and HM formulated films: a) HM-1%SA; b) HM-0.1% SA; c) HM; d) HM-20% PEG; e) HM-40% PEG;

The granular structure due to aggregates, characteristic of pure HM, disappears progressively as stearic acid content increases. This effect is proposed to be due to migration of stearic acid molecules to the film surface (Yang and Paulson, 2000). For high stearic acid content, the formation of a homogeneous layer is suspected. Surface migration of stearic acid to the surface results from a phase separation between hydrophobic SA molecules and HM polymer matrix. These results agree with contact angle measurements and surface energy determination. Concerning PEG additive, a variation of the characteristic size of the clusters is observed after incorporation of 20% PEG. The addition of larger amount of PEG into HM films increases significantly the clusters size and an average value of 70 nm is measured for 40% of PEG. The variation of clusters characteristic sizes is proposed to be due to insertion of PEG chains within HM aggregates, and consequently, increases HM clusters characteristic sizes. These results agree with T_g measurements, contact angle measurements and surface energy determination.

3.4 Nano-adhesion and nano-friction of HM and HM formulated films

The effects of stearic acid content and polyethylene glycol content on nano-adhesion and nano-friction properties of HM formulated films were investigated by AFM force curves experiments. The results are reported in Figure 4.

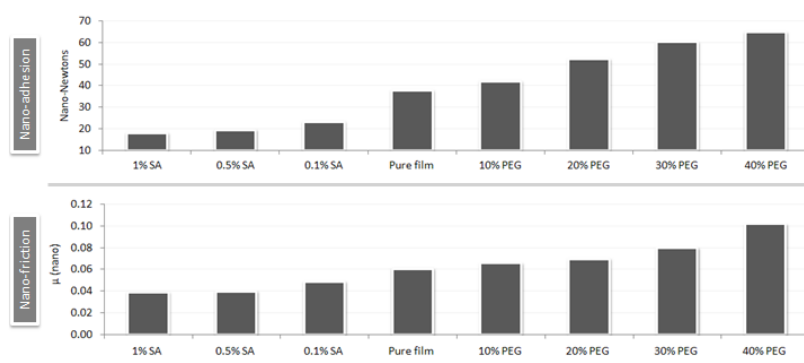


Figure 4: Effect of stearic acid and polyethylene glycol content on nano-adhesion and nano-friction of HM films.

The results show that adhesion force at the nanoscale and nano-friction coefficient decrease when stearic acid content increases. These effects can be attributed to, first, the decrease of surface energy and, second, to the role of lubricant of SA molecules that migrate to the surface of HM-SA formulated films. AFM force-distance experiments show that the adhesion force at nanoscale has a linear evolution with PEG content. Incorporation of PEG chains, miscible with HM and having a surface energy higher than HM, increases logically the interaction force between the film surface and the AFM probe. Moreover, the simultaneous capillary condensation of water molecules on the film surface due to the addition of PEG increases the contact area between the AFM probe and the film surface. Both effects increase the adhesion force at nanoscale.

4. Conclusions

In the present work, the bulk and surface physicochemical properties of hypromellose (HM) formulated films were investigated. The incorporation of additives to HM affects the films surface energy, morphology, adhesion and friction behaviours. Additives having very different hydrophobic/hydrophilic characters may constitute an asset to illustrate what is possible to happen on films surface in formulated systems. For HM films containing stearic acid (SA), the surface topography becomes smoother with SA content, due to the formation of a SA weak boundary layer. Wettability measurements have confirmed an increase of the surface hydrophobicity and a decrease of the surface energy. At nanoscale, AFM experiments in contact mode have demonstrated that the addition of stearic acid decreases both nano-adhesion and nano-friction. Incorporation of PEG into HM films induces also changes on surface morphology, hydrophobic/hydrophilic character, adhesion and friction characteristics. The variations observed suggest an insertion of PEG molecules in HM matrix, inducing an increase of clusters sizes. Thus, PEG plays the role of a plasticizer by insertion mechanism within HM matrix. Concerning the adhesion properties, the hydrophilic character of PEG leads to increase surface energy and both nano-adhesion and nano-friction.

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