



Blomstedt, M. and Vuorinen, T. (2007) Modification of softwood kraft pulp with carboxymethyl cellulose and cationic surfactants. *J. Wood Sci.* **53**(3): 223-228.

Reprinted with permission of Springer Japan.

The original publication is available at www.springerlink.com

<http://www.springerlink.com/openurl.asp?genre=article&id=doi:10.1007/s10086-006-0856-6>

© 2007 by authors and © 2007 Springer Japan

Modification of softwood kraft pulp with carboxymethyl cellulose and cationic surfactants

Minna Blomstedt · Tapani Vuorinen

Helsinki University of Technology, Laboratory of Forest Products Chemistry,

P.O.Box 6300, FI-02015 TKK, Finland

Tel. +358-9-4515110; Fax +358-9-4514259

e-mail: minna.blomstedt@tkk.fi

Key words Surface modification of softwood kraft pulp · Carboxymethyl cellulose (CMC) ·
Cationic surfactants · Sheet and fiber properties · Environmental scanning electron
microscopy (ESEM)

Abstract An ECF-bleached softwood kraft pulp was treated first with a carboxymethyl cellulose (CMC, degree of substitution 0.3, 1% on pulp) and then with alkyltrimethylammonium bromides (alkyl chain lengths of C₁₀TAB to C₁₆TAB). Surprisingly, the treatment with dodecyltrimethylammonium bromide (C₁₂TAB) markedly increased the internal and tensile strengths of the handsheets prepared from the modified pulp. Electron microscopy (ESEM) showed that these properties could be partly explained by the “rope/gumlike” bridges that were formed between the fibers.

Introduction

Sodium carboxymethyl cellulose (NaCMC or more commonly only CMC) is an anionic polyelectrolyte derived from cellulose and one of the most important cellulose derivatives. In papermaking CMC is used as a wet end additive, for surface sizing and as a component of coating colours.¹ Anionic polyelectrolytes do not generally attach on cellulosic fibers because of the electrostatic repulsion between the negatively charged cellulosic surfaces and the anionic polyelectrolyte. Previous studies conducted in this laboratory have showed that CMC grades with a low degree of substitution (DS) are irreversibly sorbed on the external surface of chemical wood pulps²⁻⁴ in the same way as wood xylans.^{5,6} The amount of CMC sorbed on pulp depended on several factors, including the degree of polymerization (DP), DS, and charge of CMC, pH and ionic strength of the sorption medium and the beating level of the pulp.² The sorption of CMC on cellulose pulps improved the strength properties of handsheets³, because the CMC treatment greatly increased the interfiber bonding in handsheets. Because CMC may adopt a similar chain conformation with crystalline cellulose,

the sorption of CMC with a low DS is probably enabled by this conformational change, as in the case of wood xylans.^{5,6} Later, other studies⁷ have shown that the sorption of CMC with a higher DS can be enhanced by adding a calcium salt.

CMC is a polyelectrolyte and polyelectrolytes tend to form micellar aggregates or micelle-like clusters with surfactants of opposite charge. The present understanding of polymer/surfactant interactions in aqueous solution has been summarised in several reviews.⁸⁻¹⁰ Concerning CMC, the driving force of the aggregation (co-operative) of cationic surfactants with CMC has been found to be of electrostatic and hydrophobic origin, i.e. the association was strengthened as the hydrophobic chain length of the surfactant or the charge density of the polysaccharide increased.^{11,12} In general, the cooperativeness also depends on the other features of the polyelectrolyte, such as the flexibility of the chains and the hydrophobic character of the repeating unit.^{13,14} An added electrolyte in the polyelectrolyte-surfactant system makes the electrostatic interactions less important and thus weakens the attraction between the polymer and the surfactant.^{8,15} Addition of salt can also stabilize the surfactant aggregates or it may, on the other hand, induce the growth of micellar aggregates, thus leading to initiation of interpolymer complexes.¹⁶ Interactions between CMC and cationic surfactants have been studied in the presence and absence of salts, showing the interaction to be strongly co-operative in nature.¹⁷ The effect of a non-ionic surfactant to the CMC-cationic surfactant system has also been studied.¹²

Although CMC and surfactants are well known chemicals in the pulp and papermaking industry, only a few attempts have been made to study the combined effect of CMC and surfactants on paper properties. The present paper examines the surprising effects of cationic

surfactants (alkyltrimethylammonium bromides) on the papermaking properties of a softwood pulp modified with CMC. The structures of the handsheets were further investigated by ESEM.

Materials and methods

Pulp

The experiments were carried out with an industrial ECF bleached spruce (*Picea abies*) kraft pulp. The pulp was obtained from a mill in the form of dry pulp sheets. The pulp was soaked in water and disintegrated (ISO 5263-1) and then refined (2000 revolutions) in a PFI mill (ISO 5264-2).

Carboxymethyl cellulose

The commercial CMC sample, Nymcel ZSB-16, was obtained from Noviant. The degree of substitution was 0.32 and the degree of polymerization (DP_v) 700 for the CMC grade used.

Sorption of CMC on pulp

Because the CMC grades applied were partly insoluble in water, stock CMC solutions (< 10 g/L) were prepared in 2.5 M sodium hydroxide. The refined pulp was mixed with water and the stock CMC solution to obtain a final pulp consistency of 5% (50 g/L) and an initial CMC concentration of 0.5 g/L (1% on pulp).² The sorptions (pH 12.5) were carried out in glass beakers. The temperature was raised to 60°C in 10 minutes. After 60 minutes, the pulp samples were cooled, filtered and washed with deionized water.

Samples of the liquid phase were withdrawn (about 100 mL) after the sorption, filtered with 0.2 µm membranes and then analyzed for dissolved carbohydrates by the phenol-sulphuric acid test.¹⁸ The reference pulps were treated under similar conditions but without CMC. Thus, the results of the phenol-sulphuric acid test were corrected for polysaccharides other than CMC. Two reference and CMC-sorption batches were prepared.

Sorption of surfactant on pulp

The pulp was modified as described above. The surfactants used in the experiments were alkyltrimethylammonium bromides ($C_nH_{2n+1}N(CH_3)_3Br$, n=10, 12, 14 and 16, denotes C₁₀TAB, C₁₂TAB, C₁₄TAB and C₁₆TAB respectively) from Fluka and were used without further purification. The surfactant added to the diluted pulp suspension before sheet making was 0.02-0.2% on fibers. Sorption experiments were also carried out with addition of sodium chloride (0.05 M NaCl). After electrolyte and surfactant addition, the pulp was allowed to stabilize for one hour.

Papermaking properties

The laboratory sheets were prepared by the standard method ISO 5269-1, with the exception of wet pressing at 490 ± 20 kPa (4 min.) and drying in a drum dryer at 60°C for 2 h. The handsheets were prepared in deionized water at a temperature of about 10°C .

The grammage of the sheets was determined by standard method ISO 536, density and thickness according to ISO 534. The light scattering coefficient was measured with an Elrepho reflectometer by standard method ISO 5631. The tensile strength of the laboratory sheets was determined with a tensile testing machine (MTS 400M) according to SCAN-P 38:80. Tearing resistance (out-of-plane tear, Elmendorf) was determined according to the standard method ISO 1974. Bonding ability (internal strength) was measured according to Tappi 833 pm-94.

Environmental scanning electron microscopy

Environmental scanning electron microscopy (ESEM) images of the paper sheets were taken with an ElectroScan ESEM 2020 instrument.¹⁹ The images were taken in the ESEM mode with GSED (gaseous secondary electron detector) at the temperature of about 23°C . Low-acceleration voltage (10kV) was used to prevent degradation of cellulose.²⁰ The pressure in the chamber was 5 torr, the condenser lens setting 40% and magnification 500-1000x.

X-ray photoelectron spectroscopy

X-ray photoelectron spectroscopy analysis (XPS) measurements were performed with a Kratos Analytical AXIS 165 electron spectrometer using a monochromated Al K α X-ray source. In order to average over the heterogeneity of the sample, survey scans and high-resolution regional spectra were recorded from at least three measurement points in each sample. All spectra were collected at an electron take-off angle of 90° from sample areas less than 1 mm in diameter. The experimental procedure has been described in more detail by Johansson et al.²¹

Contact angle measurements

Contact angle measurements of single pulp fibers (Wilhelmy technique) were carried out using a modification of the method described in.²² The fibers were suspended in the liquid/air interface from a KSV Instruments Ltd Sigma 70 tensiometer connected to a microcomputer. Twelve generally straight and undamaged fibers per sample were selected and folded at one end into a thin sheet of aluminium. The force acting on the fiber as it advanced and receded through a liquid interface was recorded automatically as a function of the depth of immersion. The solvent probe was water (ultra-high-quality water, UHQ) and used to calculate the surface tension. The measured surface tension was 71.8 ± 0.5 mN/m.²³ The maximum immersion depth was 0.7 mm and the velocity 0.9 mm/min. Measurements were carried out in an air-conditioned cabinet at room temperature. Three measurements were performed on each

fiber. The method is described in more detail in the publications by Laine et al. and Koljonen et al.^{23,24}

Results and discussion

Sorption of CMC on pulp

The degree of sorption of CMC on pulp was evaluated by estimating the content of CMC in the sorption liquid by the phenol-sulphuric acid test. Most of the CMC added (approximately 80%) was sorbed on the beaten softwood pulp fibers.

Fiber properties of pulps treated with CMC

The contact angles for single fibers were measured for the CMC-surfactant-modified and reference pulps (Fig. 1). All the fibers measured were hydrophilic. The variation between different samples, however, is within the experimental error. The contact angle values for the unmodified spruce kraft pulp (REF) agree quite well with the values reported by Koljonen et al.²³

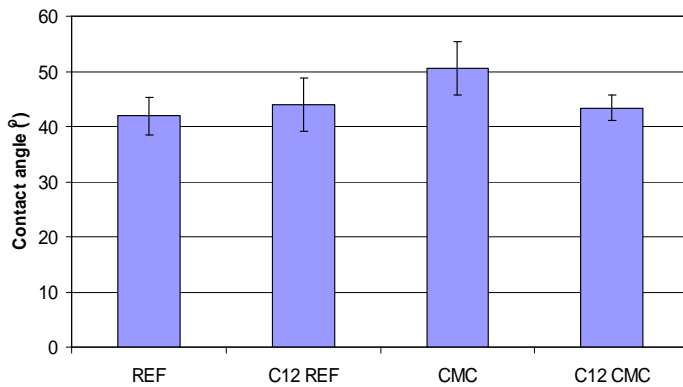


Fig. 1. Contact angles of single beaten (PFI 2000) fibers when the solvent probe was water. Abbreviations: REF= reference fibers, C₁₂ REF= reference fibers treated with 0.1% C₁₂TAB, CMC= fibers treated with CMC (addition 1% on fibers, DS 0.32), C₁₂ CMC= fibers treated with CMC and C₁₂TAB.

Sheet properties of pulps treated with CMC

Detailed sheet properties of the pulps treated with CMC and alkyltrimethylammonium bromide surfactants, with alkyl chains of C₁₀TAB, C₁₂TAB, C₁₄TAB, C₁₆TAB, and of the corresponding reference pulps are illustrated in Appendix 1. The bonding strength (internal strength, tensile strength) and sheet density increased when the pulps were treated with CMC and some of the surfactants in water. In contrast, the tear strength decreased when the pulps were modified with CMC and the surfactants.

The internal strength increased the most when the surfactant C₁₂TAB (dodecyltrimethylammonium bromide, C₁₂H₃₄BrN) was added (Fig. 2). Half of the maximum increase in internal strength was achieved only after adding 0.02% surfactant on fibers. Over 0.05% surfactant addition on fibers did not improve the sheet properties further, but caused foaming in sheet making. Meanwhile, when the surfactants C₁₄TAB and C₁₆TAB were added

the internal strength increased in the same way as for C₁₂TAB in the beginning but started to drop dramatically after adding 0.1% surfactant on fibers. For the reference pulps the surfactant treatment did not improve the internal strength values at all.

According to the study by Barck et al., the association of the surfactant with the polymer chain increases when the chain length of the surfactant increases.¹¹ In other words, this could explain in our case why the internal strength values of C₁₀TAB are so low (under the critical association concentration). Other properties also influence the association between surfactant and polymer, such as the charge density of the polyelectrolyte and the addition of electrolyte. However, none of these properties influencing the association between surfactant and polymer explains why C₁₂TAB gives the highest internal strength values (Figs. 2 and 3).

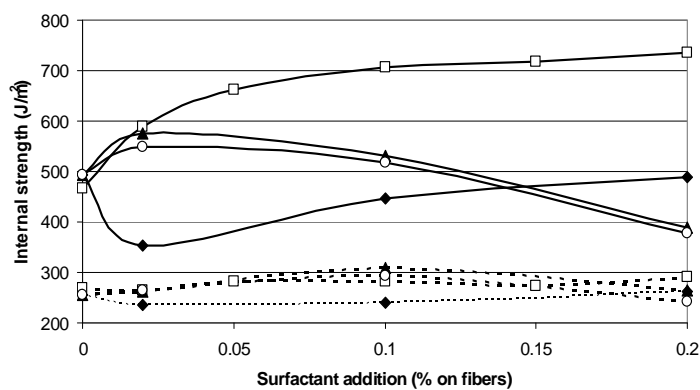


Fig. 2. Effect of treating beaten (PFI 2000) pulps with CMC (addition 1%, pH 12.5, DS 0.32) and surfactants (C₁₀TAB, C₁₂TAB, C₁₄TAB, C₁₆TAB) on internal strength of handsheets. The solid lines denote the CMC-treated pulps and the dashed lines the reference pulps (REF). The lines denote changes caused by increasing the addition of surfactant (0, 0.02, 0.05, 0.1, 0.15 and 0.2% on fibers). Abbreviations: filled diamond (◆) C₁₀TAB, open square (□) C₁₂TAB, filled triangle (▲) C₁₄TAB, open circle (○) C₁₆TAB.

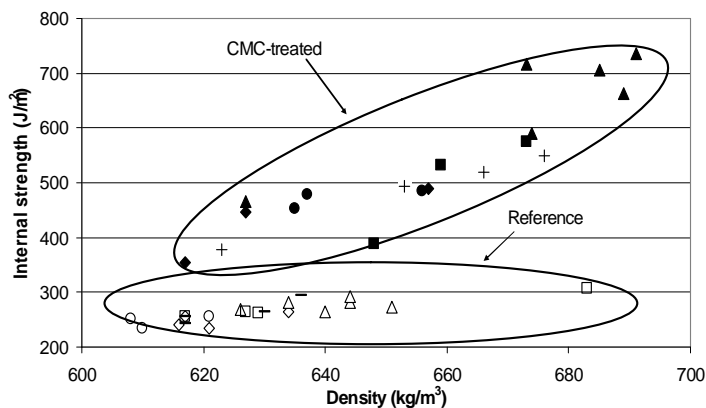


Fig. 3. Effect of treating beaten (PFI 2000) pulps with CMC (addition 1%, pH 12.5, DS 0.32), electrolyte (0.05 M sodium chloride) and surfactants (C_{10} TAB, C_{12} TAB, C_{14} TAB, C_{16} TAB) on sheet density and internal strength. Abbreviations: open diamond (\diamond) C_{10} REF, filled diamond (\blacklozenge) C_{10} CMC, open triangle (Δ) C_{12} REF, filled triangle (\blacktriangle) C_{12} CMC, open square (\square) C_{14} REF, filled square (\blacksquare) C_{14} CMC, line (-) C_{16} REF, plus (+) C_{16} CMC, open circle (\circ) C_{12} REF salt, filled circle (\bullet) C_{12} CMC salt.

A trend in papermaking is towards increased recycling of drainage waters, hence there is growing interest in knowing what effects the higher electrolyte concentrations have on paper properties. Therefore, the effect of an electrolyte on the sheet formation was investigated by preparing the laboratory sheets in water and in dilute solutions of sodium chloride (0.05 M NaCl). The internal strengths of the CMC-treated pulps were much higher than those of the corresponding reference pulps (Fig. 2). When the handsheets were prepared from slurries of C_{12} TAB-CMC-treated pulp fibers in the presence of sodium chloride, the strength properties dropped to the same level as for the other surfactants (C_{10} TAB, C_{14} TAB, C_{16} TAB) as can be seen in Fig. 3. Meanwhile, the density was clearly decreased and almost all the positive effects of adding the surfactants gained in water were eliminated when salt was added before sheet-making (Appendix 1 and Fig. 3). However, the density was not so sensitive to the electrolyte addition as it was in the study by Mitikka et al.^{2,3} Furthermore, the addition of CMC increased the internal strength also when the comparison was made at a constant density, as shown in

Fig. 3. Meanwhile, all the reference samples were gathered in the same cluster, with internal strengths below 300 J/m^2 .

Only a few attempts have been made to study the effect of surfactants on paper properties. The main effect of adding surfactants to mechanical and chemical pulps^{25,26} and sulphite pulp²⁷ was a decrease in strength properties. In most studies the light scattering coefficient increased when surfactants were added, although our study show a slight decrease in the light scattering coefficient when the pulp was surfactant-CMC-modified. The interactions between surface-active substances and sulphite and sulphate pulps are discussed in the publication by Friberg et al.²⁸ More recently, Alila and co-workers have studied the surface charge effects of adsorption of a cationic surfactant onto cellulosic fibers.²⁹

To shed more light on the superior sheet properties presented above, the structure of the sheets was investigated by ESEM (Environmental scanning electron microscopy). When the surfactant (C_{12}TAB) was added in the sheet-making stage, the ESEM images of the sheets showed strong “gum/ropelike” fibril bridges between the fibers (Fig. 4). These strong bridges may at least partly explain the improved strength properties of the handsheets prepared. In contrast, the reference sheets were very clean and bridges were hard to find on the surface of the fibers (Fig. 5).

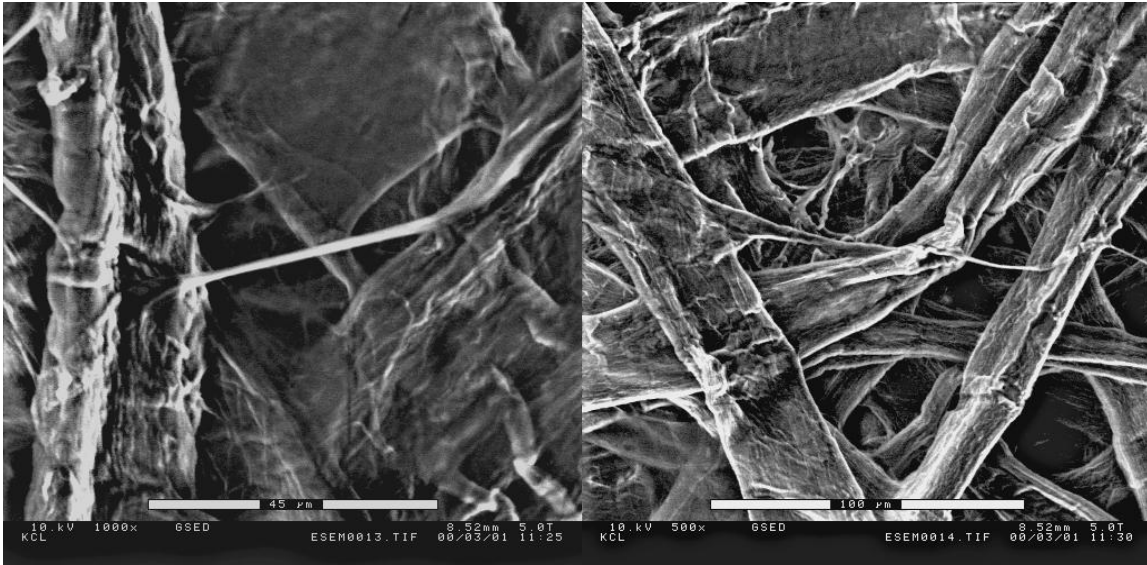


Fig. 4. ESEM images of handsheets prepared from a beaten (2000 revolutions) and CMC-treated (addition 1%, DS 0.32) pulp sheeted in water when 0.1% C₁₂TAB was added on fibers. Strong ropelike fibril bridges between the fibers are visible in both the images.

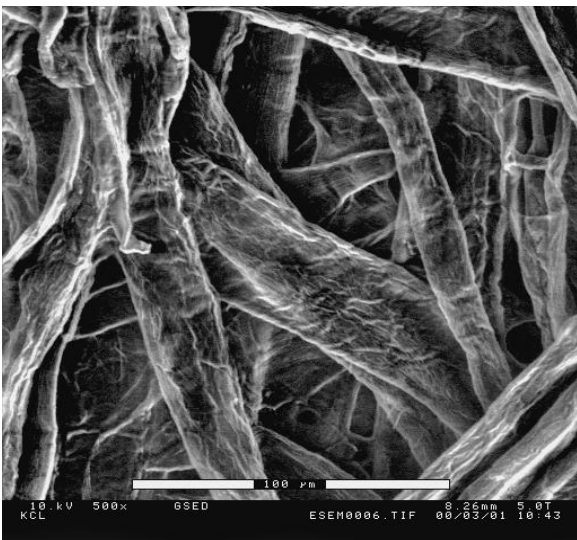


Fig. 5. ESEM images of handsheets prepared from a beaten (2000 revolutions) and CMC-treated (addition 1%, DS 0.32) pulp sheeted in water with no surfactant added. Typical of the sheets are a clean fiber surface and only a few fibril bridges were found on the surface of the fibers.

Previous studies in this laboratory^{2,3} have examined fibers treated with CMC in the presence and absence of salt with the aid of ESEM. To summarise, the ESEM images clearly showed that each chemical added created different types of bonds between fibers. The addition of CMC created a smooth (chemical) “membrane” on top of the fibers, forming a net of long bridges between fibers.^{2,3} In contrast, addition of a surfactant created long and tough bridges between the fibers (Fig. 4). Furthermore, in most of the images the bridges caused by addition of the surfactant are linked to the fibers by a multi-pillar foot.

The surface contents of the cationic surfactants were estimated to be about 2-6% analyzed by XPS (Table 1). The surfactants were clearly enriched on the surface, their surface coverage increasing with the chain length of the surfactant. Meanwhile, no actual correlation was seen between the XPS results and the internal strength on the handsheets.

Table 1. XPS results for pulp treated with CMC (ZSB-16, 1% added on fibers) and cationic surfactants. The first two data columns show the carbon and aliphatic carbon contents of the samples.

Sample	<C> ^a (%)	<C-C> ^b (%)
CMC water	56.2	6.0
CMC C ₁₂ TAB 0.02%	57.4	7.7
CMC C ₁₂ TAB 0.05%	57.2	7.7
CMC C ₁₂ TAB 0.1%	57.4	9.5
CMC C ₁₄ TAB 0.1%	58.3	10.1
CMC C ₁₆ TAB 0.1%	58.1	11.4

^a from wide spectrum, ^b from high-resolution regional spectrum

One important thing to remember is that CMC is first permanently attached on the surface of the fibers and then the surfactants are added. Therefore, it is very unlikely that a CMC-surfactant phase does exist in this fiber-CMC-surfactant system. Both cellulose and CMC

polymer chains are quite stiff. Therefore, it is improbable that any micellar aggregates are formed in the fiber-CMC-surfactant system. One theory could be that the surfactants (alkyltrimethylammonium bromides) associate with CMC on the anionic fiber surface by ionic and hydrophobic interactions. But further research is needed to clarify the interaction between the fiber-CMC-surfactant system.

Conclusions

CMC and cationic surfactants open up new possibilities for the modification of cellulosic fibers and their paper product properties. The main advantages indicated by these preliminary experiments are good internal strength of the paper.

Cationic surfactants can be easily attached to the surface of CMC-modified anionic fibers. Surprisingly, this treatment can substantially improve the internal strength of the handsheets prepared. The strong fibril bridges between the fibers revealed by the ESEM images may partly explain the increased bonding strength. When salt was added before the pulps were formed into sheets, the tensile strength and density of the sheets stayed at quite a high level, even if the internal strength decreased dramatically.

Further studies are necessary to explain the interaction between the fiber-CMC-surfactant system and the reason why the strength properties are improved when CMC and surfactants are added.

Acknowledgements This work was financed mainly by the National Technology Agency (TEKES) in Finland. The research formed a part of a large national programme related to cellulose pulps, which was also sponsored by Andritz, M-real, Myllykoski Paper, Stora Enso, UPM-Kymmene and Metso. The authors would like to acknowledge Tiina Pöhler (KCL) and Dr. Leena-Sisko Johansson (TKK) for the ESEM images and XPS analysis of the paper sheets. Thanks are also due to Mrs. Emma Matikainen for her help in the laboratory work and Dr. Monika Österberg, Dr. Eero Kontturi for their valuable comments.

References

1. Holmbom B, Stenius P (2000) Analytical methods. In: Gullichsen J, Paulapuro H, Stenius P (eds) Papermaking science and technology, Forest Product Chemistry. Fapet Oy, Helsinki, pp 107-169
2. Mitikka-Eklund M, Halttunen M, Melander M, Ruuttunen K, Vuorinen T (1999) Fibre engineering. In: 10th International Symposium on Wood and Pulping Chemistry, June 7-10, Yokohama, pp 432-439
3. Blomstedt M, Mitikka-Eklund M, Vuorinen T (2006) Simplified modification of bleached softwood pulp with carboxymethyl cellulose. Submitted for publication
4. Blomstedt M, Vuorinen T (2006) Fractionation of CMC-modified hardwood pulp. *Appita* 59:44-49

5. Mitikka-Eklund M (1996) Sorption of xylans on cellulose fibres. Lic. Thesis, University of Jyväskylä, Jyväskylä, Finland, pp 76
6. Mitikka M, Teeäär R, Tenkanen M, Laine J, Vuorinen T (1995) Sorption of xylans on cellulose fibers. In: 8th International Symposium on Wood and Pulping Chemistry, June 6-9, Helsinki, pp 231-236
7. Laine J, Lindström T, Glad-Nordmark G, Risinger G (2000) Studies on topochemical modification of cellulose fibres Part 1. Chemical conditions for the attachment of carboxymethyl cellulose onto fibres. Nord. Pulp Pap. Res. J. 15:520-526
8. Goddard ED, Ananthapadmanabhan KP (1992) Interactions of surfactants with polymers and proteins. CRC Press, Inc., Florida
9. Kwak JCT (1998) Polymer-surfactant systems, Surfactant science series volume 77. Marcel Dekker, Inc., New York
10. Jönsson B, Lindman B, Holmberg K, Kronberg B (1998) Surfactants and polymers in aqueous solution. Biddles Ltd, Guildford and Kings Lynn, UK
11. Barck M, Stenius P (1994) Interactions between carboxymethyl cellulose and cationic surfactants. 1. Phase equilibria and surface tensions. Colloids Surf., A: Physicochemical and Engineering Aspects 89:59-69
12. Gupta S, Moulik SP, Das AR (1991) Physicochemical behavior of the sodium salt of carboxymethylcellulose in dye, salt and surfactant environments. Makromol. Chem. 192:447-460

13. Thalberg K, Lindman B, Karlström G (1990) Phase diagram of a system of cationic surfactant and anionic polyelectrolyte: tetradecylmethylammonium bromide-hyaluronan-water. *J. Phys. Chem.* 94:4289-4295
14. Thalberg K, van Stam J, Lindblad C, Almgren M, Lindman B (1991) Time-resolved fluorescence and self-diffusion studies in systems of a cationic surfactant and an anionic polyelectrolyte. *J. Phys. Chem.* 95:8975-8982
15. Thalberg K, Lindman B, Karlström G (1991) Phase behavior of a system of cationic surfactant and anionic polyelectrolyte: the effect of salt. *J. Phys. Chem.* 95:6004-6011
16. Dubin PL, Vea MEY, Fallon MA, The SS, Rigsbee DR, Gan LM (1990) Higher order association in polyelectrolyte-micelle complexes. *Langmuir* 6:1422-1427
17. Hayakawa K, Kwak JCT (1983) Study of surfactant-polyelectrolyte interactions. 2. Effect of multivalent counterions on the binding of dodecyltrimethylammonium ions by sodium dextran sulfate and sodium poly(styrene sulfonate) in aqueous solution. *J. Phys. Chem.* 87:506-509
18. Dubois M, Gilles KA, Hamilton JK, Rebers PA, Smith F (1956) Colorimetric method for determination of sugars and related substances. *Anal. Chem.* 28:350-356
19. Danilatos GD (1993) Introduction to the ESEM instrument. *Microsc. Res. Tech.* 25:354-361
20. Forsberg P, Lepoutre P (1994) Degradation of pulp fibers under electron beam. *Nord. Pulp Pap. Res. J.* 9:245-247, 270

21. Johansson L, Campbell JM, Koljonen K, Stenius P (1999) Evaluation of surface lignin on cellulose fibers with XPS. *Appl. Surf. Sci.* 144-145:92-95
22. Hodgson K, Berg JC (1988) Dynamic wettability properties of single wood pulp fibres and their relationship to absorbency. *Wood Fiber Sci.* 20:3-17
23. Koljonen K, Stenius P (2005) Surface characterisation of single fibres from mechanical pulps by contact angle measurements. *Nord. Pulp Pap. Res. J.* 20:107-113
24. Laine J, Hynynen R, Stenius P (1997) The effect of surface chemical composition and charge on the fibre and paper properties of unbleached and bleached kraft pulps. In: *Fundamentals of papermaking materials - 11th fundamental research symposium, September 21-26, Cambridge, pp 859-892*
25. Christensen PK (1969) The effect of surfactants on paper properties. *Norsk Skogindustri* 23:267-275
26. Bruun HH, Enqvist R, Friberg S (1975) Influence of adsorbed surface active substances on the properties of paper. *Svensk Papperstidn.* 78:512-516
27. Touchette RV, Jenness LC (1960) Effect of surface-active agents on drainage and physical strength of sulfite pulp. *Tappi* 43:484-489
28. Friberg S, Bruun HH, Enqvist R (1975) Interaction between surface active substances and pulp fibers. *Svensk Papperstidn.* 78:517-522
29. Alila S, Boufi S, Belgacem MN, Beneventi D (2005) Adsorption of a cationic surfactant onto cellulosic fibers I. Surface charge effects. *Langmuir* 21:8106-8113

Appendix 1. Sheet properties of beaten softwood pulp with and without sorbed CMC (DS 0.32) on the surface and the effect of the surfactants added.

Sample/ Added surfactant amount (% on fibers)	Grammage (g/m ²)	Thickness (μ m)	Density (kg/m ³)	Light scattering coefficient (m ² /kg)	Tear index (Nm ² /kg)	Tensile index (Nm/g)	Internal strength (J/m ²)
REF C₁₀TAB							
0	62.8	102	617	22.3	21.2	52.4	255.1
0.02	63.8	103	621	22.4	21.1	48.9	234.7
0.1	63.0	102	616	22.4	21.2	51.2	240.6
0.2	63.9	101	634	22.2	24.0	53.0	263.3
CMC C₁₀TAB							
0	67.3	103	653	20.2	12.7	73.6	493.4
0.02	65.1	106	617	22.2	15.8	62.8	354.3
0.1	64.1	102	627	21.9	15.0	63.4	446.6
0.2	64.3	97.8	657	21.1	13.1	70.9	488.3
REF C₁₂TAB*							
0	65.0	104	626	21.8	21.1	56.2	267.9
0.02	64.5	101	640	21.2	18.4	69.4	264.6
0.05	65.2	101	644	21.3	20.9	58.2	281.2
0.1	64.5	102	634	21.5	19.2	56.9	281.4
0.15	65.3	100	651	21.3	20.1	57.7	273.6
0.2	64.8	101	644	21.6	18.9	61.3	291.1
CMC C₁₂TAB*							
0	62.2	99.2	627	20.6	12.6	85.3	466.5
0.02	64.4	95.5	674	19.4	10.9	87.6	589.5
0.05	65.4	94.8	689	19.3	11.5	87.3	663.3
0.1	64.3	93.8	685	18.5	10.8	84.6	706.6
0.15	63.3	94.2	673	19.2	11.4	88.7	717.5
0.2	65.9	95.3	691	18.4	10.1	82.5	735.5
REF C₁₂TAB+Salt							
0	64.4	106	608	22.8	20.7	52.1	250.4
0.1	64.4	106	610	22.6	20.5	46.7	235.1
0.2	63.8	103	621	22.3	20.9	50.3	256.3
CMC C₁₂TAB+Salt							
0	65.5	99.8	656	20.2	11.2	80.0	484.7
0.1	64.9	102	635	21.2	12.2	81.0	453.9
0.2	64.0	100	637	20.9	13.5	76.6	478.8
REF C₁₄TAB							
0	62.8	102	617	22.3	21.2	52.4	255.1
0.02	66.2	105	629	22.1	19.4	59.8	262.0
0.1	68.9	101	683	20.0	18.2	57.4	308.1
0.2	64.4	103	627	21.9	21.6	51.1	263.7
CMC C₁₄TAB							
0	67.3	103	653	20.2	12.7	73.6	493.4
0.02	65.3	97	673	19.6	10.6	79.1	575.3
0.1	67.0	102	659	19.5	13.0	60.1	531.7
0.2	65.7	101	648	20.8	14.2	66.1	389.2

REF C ₁₆ TAB							
0	62.8	102	617	22.3	21.2	52.4	255.1
0.02	63.7	101	630	21.5	19.2	54.8	265.0
0.1	61.5	96.8	636	22.1	18.0	57.5	293.6
0.2	64.0	104	617	22.8	22.1	48.4	242.7
CMC C ₁₆ TAB							
0	67.3	103	653	20.2	12.7	73.6	493.4
0.02	65.6	97	676	20.0	11.3	83.2	548.7
0.1	67.8	102	666	19.6	12.2	67.2	518.7
0.2	67.2	108	623	21.6	18.8	55.7	377.8

REF= no CMC added, CMC= CMC-treated pulp, Salt= 0.05 M NaCl added, * second sorption batch