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Carboxymethyl Cellulose Treatment As a Method to Inhibit Vessel Picking Tendency in Printing of Eucalyptus Pulp Sheets

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This article presents an industrially feasible method to effectively reduce vessel picking tendency by a simple chemical modification of pulp. ECF-bleached eucalyptus kraft pulp was treated with carboxymethyl cellulose (CMC) under specified conditions. The aim was to study the effects on vessel element structure and vessel picking tendency of the laboratory sheets prepared. In addition to the improved strength properties of the sheets, a significant decrease in vessel picking tendency was noted in the laboratory printing test. Whereas refining improved mainly the bonding ability of fibers, CMC treatment effectively enhanced the bonding of vessels as well. Moreover, filmlike structures were formed in the fibrillated areas of the CMC-treated handsheets, and they were concluded to reinforce bonding within the sheet. Also, fragmentation of vessel elements through CMC modification was found to be important and to result in a decreasing picking tendency.

1. Introduction

As a channel for conducting water and nutrients within a tree, vessel elements are essential parts of the hardwood cell matrix. However, in papermaking applications, they cause some difficulties, for instance, in the form of vessel picking phenomenon in offset printing. Because of their distinctive shape and comparatively large size, vessel elements have inferior bonding properties compared to fiber, and they are easily picked off from the paper surface because of the high splitting force in the printing nip.[1] Consequently, they attach to the printing blanket, disturbing ink transfer further, and the printing defect, appearing as white spots, can extend for even hundreds of impressions.[2] As a consequence, printing blanket washups are needed more frequently, resulting in increased downtime of the printing press.[1] Eucalyptus pulp, which otherwise has excellent properties for pulp and paper manufacturing and usage,[3−6] is especially prone to vessel picking,[3] and there is a need to control the problem efficiently and in an industrially feasible way. The purpose of this study was to investigate how a simple modification of eucalyptus pulp with carboxymethyl cellulose (CMC) results in a suppressed vessel picking tendency in the subsequent paper.

Both the hardwood content of paper and the bonding ability between fibers and vessels are relevant for the vessel picking tendency of paper.[7,8] Generally, vessel picking is controlled by pulp refining or by either stock or surface sizing.[7,9] Other possible control methods are selection of raw materials (wood species),[8] hydrocyclone separation,[10] and enzymatic treatment.[11,12]

To prevent vessel picking, it is essential to affect the bonding properties of vessel elements or, alternatively, to remove them from pulp; however, the latter has so far been estimated to be industrially impractical.[8,13] Intensive refining of pulp breaks down vessel elements[7] and ultimately improves their bonding ability, although such treatment is detrimental for other important properties, such as the drainability of the pulp and paper bulk.

During recent years, several publications[14−17] have presented the effects of irreversible attachment of carboxymethyl cellulose (CMC) on pulp without alum or cationic polymers, which are normally required to deposit the anionic CMC onto likewise anionic fibers.[18] The target is to enhance the functionality of fiber and, consequently, to improve the properties of the paper for its end use. As a result of this simple chemical modification, substantial increases in paper strength have been reported. Blomstedt et al.[19,20] stated another interesting effect of CMC modification as a decrease in apparent vessel content of pulp. Consequently, decreases in both the vessel pick number and the area were noted. However, the mechanism through which vessel picking tendency was decreased by CMC modification remained unclear. Also, the reason for the decreased apparent vessel content was not solved; it was hypothesized that either the shape or size of the vessel elements was changed or that an error occurred in the fiber analysis.

Because the previous account[20] on the effect of CMC modification on vessel picking tendency was mainly descriptive, this study investigated the effects of CMC modification of eucalyptus pulp further to clarify the mechanism behind the reduced vessel picking tendency. The emphasis is on the structural changes of vessel elements and their bonding properties within a fiber matrix. Based on laboratory printing tests, we observed that CMC modification, combined with slight refining, effectively reduces vessel picking tendency whereas refining is mainly effective in improving the bonding ability of fibers. Moreover, microscope images are presented to specifically explain the improved bonding ability of vessels and fibers after CMC modification.

2. Materials and Methods

2.1. Pulp and Carboxymethyl Cellulose. The experiments were carried out with an industrial elemental-chlorine-free- (ECF-) bleached eucalyptus kraft pulp. The pulp was refined in a Voith Sulzer LR1 research refiner (Voith Sulzer, Heiden-

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heim, Germany). The disk fillings of the refiner were 2/3−1.42−60D, which is designed for short-fiber pulps. The refining consistency was 4.0%, and the specific edge load 0.3 W s/m. The specific refining energy (SRE) levels were 0 and 30 kWh/t. The pulps included in the study were unbeaten reference (UREF), unbeaten CMC-treated (UCMC), beaten reference (BREF), and beaten CMC-treated (BCMC) pulps.

The Schopper−Riegler (SR) numbers of the pulp samples were determined according to standard method ISO 5267-1. The SR numbers for the unbeaten and beaten pulps were 13.6 and 21.9, respectively.

The commercial CMC sample, Nymcel ZSB-16, was obtained from Noviant. The structure of CMC is presented in Figure 1.

Depending on the degree of substitution (DS), the groups marked as R are substituted either by hydrogen (H) or by carboxymethyl groups (CH_2COO^-); the maximum DS is 3, in which case all hydroxyls were substituted by carboxymethyl ether groups. According to the manufacturer, the degree of substitution (DS) was 0.32, and the degree of polymerization (DP_v) was 700 for the CMC grade used. The choice of DS was based on our earlier experience with CMC sorption: CMC with a lower DS (0.2) is difficult to handle because of its extremely low solubility in water, and CMC with a higher DS (0.4) attaches poorly to the fibers.[16] A low DS is required in any case because above a DS of ~0.45 the electrostatic repulsion between the CMC and the fibers starts to obstruct the sorption. Prior to the sorption of CMC on the pulp, dry CMC powder was first diluted in 2.5 M NaOH because CMC with a low DS is insoluble in water. During the next day, distilled water was gradually added to the mixture, and the alkalinity decreased to 0.4 M. After several days of mixing, the CMC solution was centrifuged, and the supernatant was collected. The concentration of the CMC solution was 7.1 g/L, as determined by the phenol−sulfuric acid test.[21]

2.2. Fiber Properties. Fiber dimensions and deformations were analyzed with a commercial KajaaniFiberLab analyzer (Metso Automation, Kajaani, Finland). Samples were prepared according to the recommendations of the equipment manufacturer (KCL standard 225:89), and the stock consistency of the samples used to calculate the coarseness values was determined according to standard method ISO 4119. Two analyses were performed on each sample.

2.3. Sorption of CMC on Pulp. The sorption of CMC on eucalyptus pulp was performed in 2.5% pulp consistency with 1% CMC on pulp, according to the procedure published by Blomstedt et al.[17] The amount of CMC attached on the fibers was determined by the phenol−sulfuric acid test,[21] i.e., by measuring the amount of unattached CMC from the filtered liquid phase of sorption. Samples of 50 mL were withdrawn from the sorption liquid and centrifuged for 30 min before the determination of dissolved carbohydrates. Because the reference and CMC-treated pulps were treated under similar conditions, the results of the phenol−sulfuric acid test were corrected for polysaccharides other than CMC.

2.4. Water Retention Value and Papermaking Properties. Water retention values (WRVs) of the pulps were determined in accordance with standard method SCAN-C 62:00 using a GR 422 Jouan centrifuge.

The laboratory sheets were prepared in deionized water according to standard method ISO 5269-1. A conventional sheet-former was used, and the target grammage was 60 g/m^2. Wet pressing was done at 490 ± 20 kPa (4 min 20 s), and handsheets were dried in a drying drum (65 °C, 2 h). Before and during the testing of physical properties, the laboratory sheets were kept in the conditioning atmosphere [ISO 187:1990(E)].

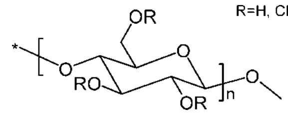

Figure 1. Structure of carboxymethyl cellulose (CMC). The degree of substitution (DS) of CMC is determined by the amount of groups marked as R, which are substituted by carboxyl groups; the maximum DS is 3.

The physical properties of the sheets were determined according to standard method ISO 5270:1998(E). Tensile strength and tensile stiffness were measured with a Tensilon UTM III 100 tensile testing machine (A&I, Tokyo) by standard method ISO 1924-2:1999(E) (the distance between the clamps was 100 mm, and the rate of elongation was 10 mm/min). Internal strength was measured with a Scott Bond tester according to test method Tappi 569 pm-00. Tensile index represents the maximum force per unit width that a paper strip can resist before breaking, corrected by the basis weight of the paper. Tensile stiffness is essentially a measure of the elastic modulus of paper, and internal strength represents the *Z*-directional strength, which reflects the ability of paper to resist tensile loading in the direction perpendicular to the plane of paper. The reader is referred to the standards for more extensive descriptions.

Optical properties were determined with a Topscan TC-1800 spectrophotometer (Tokyo Densyoku, Tokyo). ISO brightness was determined according to standard method ISO 2470:1999(E), opacity according to standard method ISO 2471:1999(E), and light-scattering coefficient according to standard method ISO 9416:1998(E). ISO brightness measures the reflectance factor, which is detected with a brightness meter whose sensitivity to light corresponds to a wavelength of 457 nm. Opacity represents the ability of a material to obstruct the passage of light, and light-scattering coefficient is a quantity related to the scattering of light according to the Kubelka−Munk theory. The reader is referred to the standards for more extensive descriptions.

2.5. Laboratory Printing Tests and Microscopic Observations. Laboratory printing tests were carried out with a KRK Multipurpose Printability Tester (Kumagai Riki Kogyo Co. Ltd., Tokyo), using commercial sheet-fed offset printing ink (TK Hy-Unity NEO Cyan MZ) obtained from Toyo Ink Co. Ltd. (Tokyo). The following parameters were used in printing: constant printing speed, 2.8 m/s; printing load, 12.3 kN/m; ink amount, 0.4 mL; inking roll temperature, 25 °C; room temperature, 20−25 °C. The ink kneading time was 2 min. Ink was transferred to the ink roll in 1 min, and before printing, the printing roll was kept at rest for 1 min. The top side of the laboratory sheet was printed because, in the case of CMC-treated pulp, some particles attached to the wire of the handsheet mold during sheet making.

Detached particles from the printing blankets were collected with adhesive tape and analyzed with an Olympus BX50 optical microscope (Olympus, Tokyo) equipped with a phase-contrast lens (Olympus UPlanFLN-PH). A digital camera (Olympus PD20) was attached to the microscope. The target was to examine the detachment patterns of vessel elements.

Microscope observations of the unprinted laboratory sheets were done with a field-emission-type scanning electron microscope (S4000, Hitachi, Tokyo). A low acceleration voltage (5 kV) was used to limit the penetration depth of the electrons that would be attenuated by the thin surface coating. Samples were coated with osmium (5-nm layer) to adhere conductance

Table 1. Results of Fiber Analysis of Reference (REF) and CMC-Treated (CMC) Eucalyptus Pulp

property	UREF	UCMC	BREF	BCMC
refining level (kWh/t)	0	0	30	30
cell wall thickness (μm)	4.4	4.4	4.3	4.4
fiber length (mm)	0.70	0.71	0.70	0.72
fiber width (μm)	16.1	15.9	16.0	15.9
curl value (%)	21.8	21.0	21.1	19.5
coarseness (mg/m)	0.076	0.071	0.074	0.072
fines content (%)	8.67	7.01	9.21	7.75
fibrillation (%)	0.78	0.66	0.98	0.79
kink (1/m)	1930	1940	1740	1630
apparent vessel content (1/m)	29.5	22.6	27.2	22.0

Table 2. General Paper Properties of the Reference (REF) and CMC-Treated (CMC) Laboratory Sheets

property	UREF	UCMC	BREF	BCMC
refining level (kWh/t)	0	0	30	30
attached CMC on pulp (mg/g)		3.52		4.87
WRV (g/g)	1.42	1.51	1.56	1.69
density (kg/m^3)	421.1	433.5	509.6	518.0
tensile index (kNm/kg)	17.3	22.2	32.1	41.9
tensile stiffness (MNm/kg)	2.4	2.7	3.4	3.8
internal strength (J/m^2)	64.9	82.1	102.9	147.4
ISO brightness (%)	88.9	88.4	87.5	87.2
opacity (%)	79.3	78.3	77.7	77.0
light-scattering coefficient (m^2/kg)	60.8	57.2	56.3	54.0

to avoid charging on the isolating sample surface. During the observations, attention was paid especially to the vessel structure and vessel-to-fiber bonding areas. Manual image analysis was done for the scanning electron microscopy (SEM) images to determine the breakage level of vessel elements in each sample. Categories of unbroken vessels, broken vessels, and pieces of vessels were used in the determination. Vessels designated as broken were partly torn, whereas the pieces of vessels were clearly small fragments.

3. Results and Discussion

3.1. Sorption of CMC on Pulp. Although anionic, CMC is sorbed to anionic fibers when the DS is low enough for the adsorption to eliminate the electrostatic repulsion. One can speculate that the sorption itself is driven by cocrystallization, a phenomenon that has been demonstrated for systems of dissolved polysaccharides (CMC in our case) and crystalline polysaccharide surfaces (crystalline cellulose microfibrils in the pulp in our case).[22,23] The amount of attached CMC was evaluated by determining the amount of unsorbed CMC in the sorption liquid. Of the added CMC (1% on the fibers), unbeaten pulp sorbed 35.2%, whereas beating of the pulp led to 48.7% sorption. Per unit weight of pulp, this means a CMC sorption of 3.52 mg/g of unbeaten pulp and 4.87 mg/g of beaten pulp. These sorption degrees were considered high enough to study the effect on vessel picking tendency, even though, according to earlier publications,[17,19] sorption degrees from 60% to 80% (i.e., from 6 to 8 mg CMC/g of pulp) for beaten hardwood pulp are common for the CMC attachment method used in this study. Generally, higher amounts of attached CMC have been reported on softwood rather than on hardwood.[24] The reason for this difference is claimed to be a higher total amount of charged groups in hardwood fibers compared to softwood fibers,[25] which increases the repulsion between the anionic CMC and the anionic hardwood fibers.

3.2. Fiber Properties. Fiber properties were analyzed with a KajaaniFiberLab instrument, and the results are reported in Table 1. An earlier publication by Blomstedt et al.[19] showed that there was an unexpected decrease in the apparent vessel content of eucalyptus pulp after CMC modification. A similar effect was found here in the form of a ca. 20% decrease in the apparent vessel content, as measured by the KajaaniFiberLab analyzer, due to the CMC modification. This surprising decrease is not an artifact of the measurement technique, as the phenomenon was independently discovered by a FiberLab analysis (this work) and by optical microscopy observations.[20] Further clarification on the issue is given in relation to electron microscopy data below. In addition, there was a decrease in the kink and curl values because of the anionic repulsion and increased hydration caused by CMC. Resulting fiber straightening was also reported in earlier studies on CMC-treated fibers.[19,26] The decrease in coarseness, fines content, and fibrillation might result from the high alkalinity during CMC treatment.

3.3. Water Retention Value and Papermaking Properties. WRVs and papermaking properties are reported in Table 2. WRV, which is related to the swelling, charge, and bonding ability of fibers,[27] increased upon both CMC modification and refining. In an earlier comparable report,[19] even higher increases in WRV were reported. However, the amounts of attached CMC were also higher in these works.

Some general paper properties were measured from the respective handsheets to enable a comparison with previous studies related to the topic. It was found that the optical properties were slightly impaired as a result of the CMC modification of pulp (Table 2). However, the effect of CMC modification was not as strong as that of refining. Moreover, in a study by Watanabe et al.,[28] even brightness increases were reported after CMC addition because of the improved retention of additives.

In the case of beaten pulps, the decrease in optical properties was combined with a strong increase in density, which implies sheet consolidation. However, with respect to a slight increase in density, CMC modification also had a rather large effect on the light-scattering coefficient. Usually, strength agents do not affect light scattering much because of an increase in the specific bond strength rather than the bonded area. In any event, extensive swelling of microfibrils on the fiber surface is believed to increase bonding after CMC modification. It is possible that the skeletal structure of the fiber network was not changed by CMC addition and, therefore, that the density remained rather stable.

As expected, both CMC treatment and refining increased the strength properties of the handsheets. Strength improvement by CMC (Table 2) was higher for beaten pulp, especially in the case of internal strength, which is partly due to the higher amount of attached CMC. According to Mitikka et al.,[14] the swelling of external microfibril bundles as a result of CMC modification increases interfiber bonding. Simultaneously, carboxyl groups introduced by CMC addition increase the bond and paper strength.

The strength improvement was the highest (43%) in internal strength (Scott-Bond) for beaten CMC-modified pulp. Tensile strength improved by ca. 30%, and tensile stiffness improved by ca. 10% compared to the corresponding reference handsheets. Even higher strength improvements were reported previously,[17,19,29] generally because of higher sheet densities, higher amounts of attached CMC, and drying of the sheets under restraint. However, in this study, the emphasis was on the vessel picking phenomenon rather than the strength improvement.

The advantage of using strength agents is generally the ability to increase strength without much affecting density. Thus, the specific bond strength is affected rather than the relative bonded

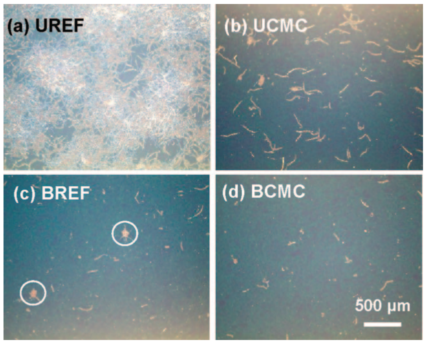

Figure 2. Light microscope images of printing blankets of each sample. Detached vessels were present in the printing blankets, except for beaten CMC-treated sample (d).

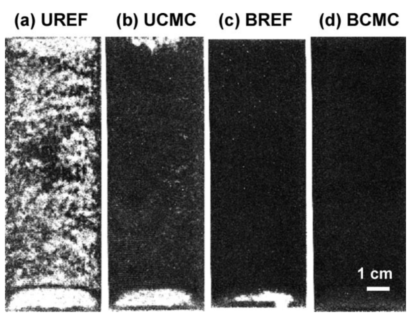

Figure 3. Scanned image of printed samples. A notable increase in surface strength is shown after both refining and CMC treatment. The BCMC sample (d) has hardly any pick marks.

area. This was the case in the studies of Laine et al.[29,30] However, in this study, CMC treatment increased paper density slightly (2−3%), and Blomstedt et al.[16,17,19] reported even higher increases in density (5−12%). The increase in density might be related to the extensive swelling of external microfibrils after CMC modification.[14] Such structures are probably susceptible to more extensive bonding. Moreover, Mitikka et al.[14] hypothesized that the flexibility of fibers increases and, as a consequence, the number of fiber−fiber bonds and sheet consolidation increase. The effect of refining on density is, as expected, clearly higher.[31]

3.4. Laboratory Printing Tests and Microscopic Observations. To study the effect of CMC modification and refining on vessel picking tendency, the sheets were printed with a laboratory-scale printability tester. After printing, optical micrographs were taken from the printing blankets to study the composition of the detached particles. From the images in Figure 2, it can be seen that the surface strength of unbeaten samples (UREF and UCMC) was too low to resist the high splitting force in the printing nip, and both fibers and vessels picked off. Refining (BREF) clearly improved the bonding ability of fibers, but despite refining, unbroken vessel elements were still clearly visible on the printing blanket. In case of sample BCMC, only a few fibers were observed on the printing blanket.

Similar conclusions can be made based on the scanned images of printed samples (Figure 3). Unbeaten samples have poor print quality because of inadequate surface strength, and despite the otherwise excellent print quality, white spots present on sample BREF indicate a vessel picking problem. The combination of CMC modification and beating (sample BCMC) was definitely the best treatment in terms of decreasing the vessel picking tendency. In this case, the printed samples contained hardly any pick marks, and the visual print quality was excellent.

Detached particles were collected from the printing blanket for further analysis with an optical microscope. The target was to determine how the vessel elements were removed (as fragments or as a whole) and whether fibers were pulled out attached to them. Optical micrographs are shown in Figure 4. As mentioned earlier, the surface strength was low for sample UCMC, and therefore, many fibers were picked off in addition to vessels. However, it was also noticed that, almost without exception, the removed vessels had some fibers attached to them. This could imply better adhesion between CMC-treated fibers and vessels. In the case of sample BREF, it was obvious that the bonding ability of the fibers was greatly improved as a result of refining and mainly vessels were picked off. Fifty percent of the vessels were removed selectively with no fibers attached to them.

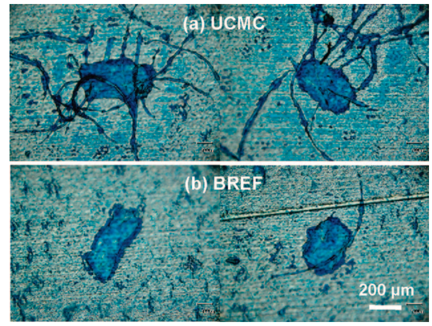

Figure 4. Detached vessel elements that were collected from the printing blanket. (a) UCMC vessels attached to several fibers and (b) BREF vessels removed almost selectively.

Based on the observation of 93 removed vessels from samples UCMC and BREF, it was found that most of the detached vessels (89%) were removed as unbroken. Therefore, breaking vessel elements prior to printing either by beating or by CMC modification can be deemed as an effective way to control vessel picking tendency. Another explanation for this hypothesis was found in the SEM observations (Figure 5), because the edges of the vessel fragments were found to be fibrillated and, consequently, prone to form bonds.

To understand the effect of CMC treatment on the bonding ability of vessels in more detail, scanning electron microscopy (SEM) was performed to analyze the unprinted handsheets. Filmlike structures were observed in the fibrillated areas of CMC-treated sheets (Figure 6). Those structures were concluded to be of great importance in improving the internal strength of CMC-treated sheets because they were clearly stronger than the fibril bridges observed in sample BREF. We can speculate that such filmlike structures emerged as a result of the increased electrostatic repulsion between the microfibrils caused by CMC addition, i.e., better dispersion of the surface microfibrils. Similar stuctures in wet pulp fibers were described earlier by Mitikka et al.[14] They stated that, as a consequence of CMC modification of pulp, external microfibrils swell extensively, forming gelated structures on fiber surfaces.

Also the breakage of vessel elements was determined by SEM to clarify the seemingly impossible decrease in apparent vessel content caused by CMC modification (Table 1). It was found that, in addition to refining, CMC treatment also decreased the percentage of unbroken vessels (Figure 7). No logical reason for the vessel breakage was found, but the results of both FiberLab analysis and microscopic observation are comparable with those published earlier by Blomstedt et al.[20] Hypothetically, vessel elements could be susceptible to breakdown because of their thin cell walls and the abundance of pores in their cell walls. Better dispersion of microfibrils upon CMC modification coupled with these fragile structural properties might contribute to vessel breakage during the agitation of CMC treatment.

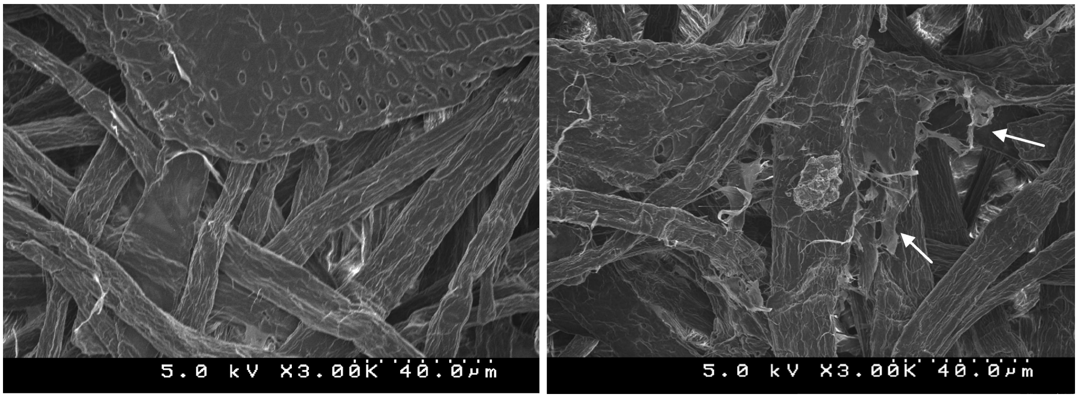

Figure 5. Exemplary images of unbroken (left) and broken (right) vessel elements of a UREF sample. The edges of the broken vessels are fibrillated and prone to bonding. Examples of fibrillated edges are indicated by arrows.

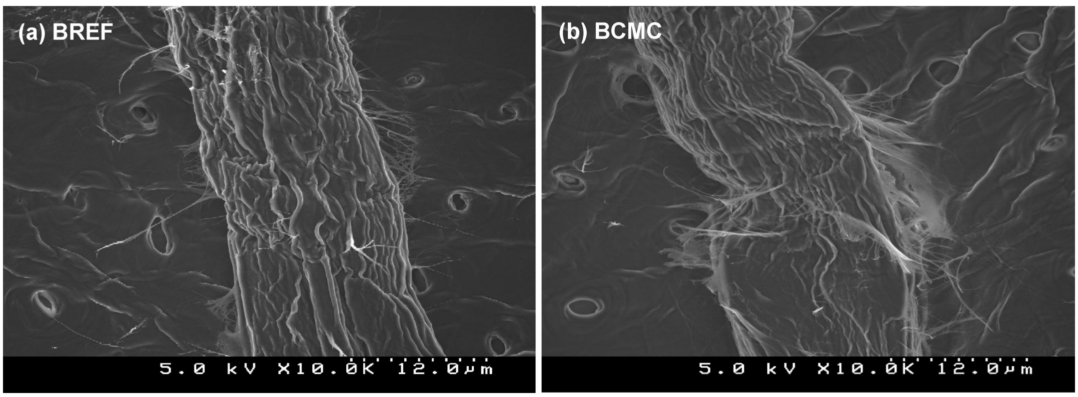

Figure 6. SEM images of handsheets prepared from beaten pulp: (a) BREF sample and (b) BCMC sample. Fibrillated areas of the CMC-treated sample have more filmlike structures present.

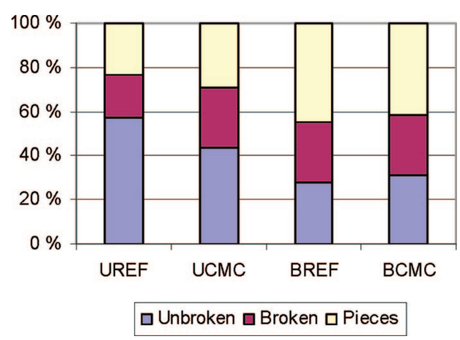

Figure 7. Distributions of unbroken vessels, broken vessels, and pieces of vessels in the reference and CMC-modified pulps, calculated by manual image analysis of SEM images.

The only difference in the treatment of reference and CMC-treated pulps was the alkalinity of solution, because CMC treatment was done under high alkalinity (pH 11.8) and the reference pulp was treated under neutral conditions. Because the breakage of vessel elements through CMC modification of the pulp was a somewhat unexpected phenomenon, the effect of high alkalinity on vessel breakage was studied separately, following the same procedure as in the case of CMC treatment. However, based on SEM observation of the unprinted handsheets, a negligible effect on vessel breakage caused by high alkalinity was noted: The ratios of unbroken vessels, broken vessels, and vessel pieces were similar within 15% tolerance, regardless of the pH.

The effects of CMC modification on vessel picking tendency are promising, and we foresee that this presented method could effectively control the problem. CMC modification also evens out the low strength potential of hardwood, which otherwise has excellent papermaking properties, e.g., formation and printability. Moreover, CMC treatment enables high strength properties without any significant loss in the bulk and light-scattering coefficient of paper. On the other hand, refining, which is commonly used to control vessel picking, dramatically affects both the light-scattering coefficient and the paper density.[31] Moreover, refining is an energy-intensive procedure and impairs other important properties, such as the drainability of the pulp and the dimensional stability of the paper. Sizing by starch, for example, is another traditional method for controlling vessel picking, although rather high starch additions have been reported as effective dosages.[9] Otherwise, the comparison of the methods is cumbersome because only a few accounts are available in literature.[9]

It is essential to optimize the conditions of the CMC treatment, so that quantitative sorption is achieved in process-realistic conditions and no chemical ends up disturbing the closed process waters. Also, the price of CMC is relatively high for stock treatments, and industrial production of technical-grade CMC with a low degree of substitution (DS) is required. The low solubility of low-DS CMC and the requirement of highly alkaline conditions are other obstacles. These technical difficulties are, however, capable of being solved, for instance, by performing the CMC treatment at a pulp mill where high alkalinity does not pose any major challenges. Moreover, optimization of the CMC modification from the vessel picking point of view is required. One possibility for future research is to explore whether adding the CMC before beating has a favorable influence in hindering the vessel picking tendency. We foresee that CMC modification has true potential to control the vessel picking phenomenon compared to the traditional control methods.

4. Conclusions

CMC modification of eucalyptus pulp led to a substantial increase in the internal strength of the laboratory sheets prepared and, additionally, resulted in a notable decrease in the vessel picking tendency. According to the investigation of printed sheets and detached particles on the printing blankets, refining was shown to be effective mainly in improving the bonding ability of fibers, whereas vessel elements remained susceptible to pick off. Slight refining combined with CMC modification was found to be an efficient way to control vessel picking and to achieve excellent print quality.

Filmlike structures present in the fibrillated surfaces of CMC-treated fibers and vessels reinforce the interfiber bonding. Those structures are a result of the disintegration of microfibrils because of the repulsion caused by CMC addition. Most of the detached vessel elements were observed to be unbroken. Thus, another reason for the decreased vessel picking tendency is the breakage of vessels through CMC modification because the edges of the vessel fragments are highly fibrillated and prone to bonding.

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