

Bleaching Microcrystalline Cellulose Using Hydrogen Peroxide, Peracetic Acid, and Ozone

Riku Kopra,^{a,*} Kari Vanhatalo,^b Sonja Päärnilä,^b Antti Pappinen,^a and Olli Dahl^c

AaltoCell™ based microcrystalline cellulose was bleached using hydrogen peroxide, peracetic acid, and ozone. The target brightness was set at 85% ISO brightness of the sheet (93% Y-brightness), which is white enough for the traditional use of microcrystalline cellulose. Both the paper pulp and dissolving pulp can be hydrolyzed using the AaltoCell™ process. Using paper pulp as a raw material, the brightness of the final microcrystalline cellulose decreased. The higher the temperature and retention time during the hydrolysis process, the greater the brightness loss. This effect can be explained by the so-called caramelization reaction. Due to this phenomenon, the microcrystalline cellulose should be bleached before using the product in food and pharmaceutical applications. The results showed that the target brightness was reached with ozone at doses of approximately 5 kg/ton with a reaction time of a few minutes; peroxide and peracetic acid required approximately twice the dose and a reaction time of at least 30 min. The concentrations of the chemical oxygen demand and total organic carbon in the pulp filtrate fraction varied with the bleaching chemicals used, with both values being low with ozone and the highest with peracetic acid.

Keywords: AaltoCell™; Acid hydrolysis; Caramelization; Bleaching; Microcrystalline cellulose

Contact information: a: FiberLaboratory, South-Eastern Finland University of Applied Sciences, Vipusenkatu 10, Savonlinna 57200 Finland; b: Andritz Ltd., Fiber Technologies Division, Tammasaarenkatu 1, Helsinki 00180 Finland; c: Aalto University, School of Chemical Engineering, Vuorimiehentie 1, Espoo 02150 Finland; *Corresponding author: riku.kopra@xamk.fi

INTRODUCTION

Microcrystalline cellulose (MCC) is partially depolymerized cellulose, with a low degree of polymerization. It is a powder-like product invented in the 1950s by Battista, patented in 1961 by Battista, and was first commercialized under the brand name Avicel® (Battista 1950). Since then, the MCC process has been studied and developed by several research groups (Toshkov *et al.* 1976; Delong 1986; Bergfeld and Seifert 1996; Ha *et al.* 1998; Hanna *et al.* 2001; Jollez *et al.* 2002; Mattheson *et al.* 2002; Schaible and Brinkman 2003; Nguyen 2004; Ioelovich and Leykin 2005; Schaible and Sherwood 2005; Nguyen and Tan 2006; Frangioni and Frangioni 2016; Tan *et al.* 2016; Valchev *et al.* 2020).

Currently, MCC is used mostly in pharmaceutical and food industry applications. All lignocellulose sources that contain crystalline cellulose can be used as a raw material for MCC. A classic process for MCC production is performed using strong acid hydrolysis and a low consistency of dissolving pulp (Battista *et al.* 1961). The degree of polymerization (DP) level of chemical pulp is typically 500 to 2000, whereas for MCC, that number is less than 400. Any MCC particles with a size lower than 5 µm must not form more than 10% of the total particles (FAO 1996). Lately, a novel way to produce MCC has been developed, called AaltoCell™; this process is performed using mild acid

hydrolysis and a short retention and has a high operating consistency (Dahl *et al.* 2016). These features enable MCC to be produced at a high capacity, and the entire production line can be installed in a chemical pulp mill. In addition, paper pulp can be used as a raw material. This allows the production of pure carbohydrates, in the form of monomers, which can be used for production of other biobased products, *e.g.*, biogas, bioethanol, PLA.

When cellulose is hydrolyzed in the traditional way *via* strong acid hydrolysis, the DP of the glucose units in the cellulose molecule chain is reduced. The acid hydrolysis product mixture contains dissolved carbohydrates. As such, 5-hydroxymethylfurfural is formed from glucose decomposition (Kupiainen 2012); it then decomposes into levulinic acid and formic acid under those conditions, and the decomposition rate is highly affected by an increase in temperature (Girisuta *et al.* 2006). Hemicelluloses degrade to form furfural, and this process is followed by further decomposition into organic acids and condensation reactions to form humin-like substances (Sumerskii *et al.* 2010).

In the AaltoCell™ process, MCC can be produced from fibrous cellulosic material *via* mild sulfuric acid hydrolysis at a consistency greater than 8% and a temperature greater than 120 °C. In addition to temperature, consistency, and a low chemical dosage, the hydrolysis process of MCC is considerably affected by the hydrolysis time. The intensity of the hydrolysis treatment greatly affects the brightness of the solid residue. This effect is determined by the time and temperature, which can be expressed as the hydrolysis factor (P-factor), which allows the comparison of hydrolysis at different temperatures, for example (Sixta 2006). With longer hydrolysis times when using paper pulp as a raw material with a constant temperature, the solid residue becomes brown in color, as shown in Fig. 1 (Vanhatalo and Dahl 2014).

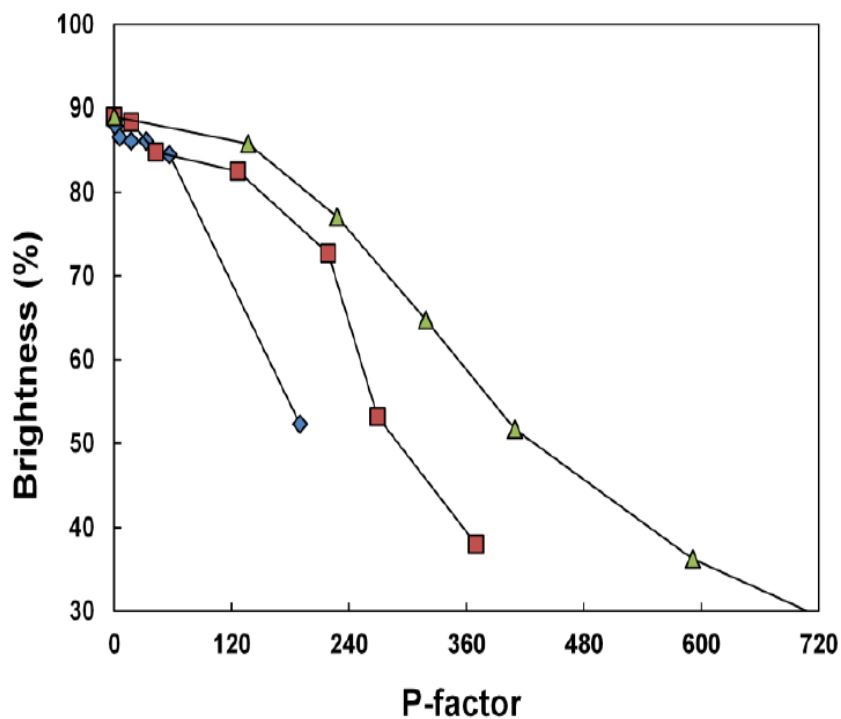


Fig. 1. The ISO brightness as a function of the P-factor. Note: the hydrolysis temperature levels were 120 °C (◆), 140 °C (■), and 160 °C (▲), the H₂SO₄ dosage was 1.5%, and the consistency was 10%; the raw material grade used was softwood paper pulp (Vanhatalo and Dahl 2014).

The phenomenon that is apparent in Fig. 1 is likely due to decomposition (dehydration) and condensation reactions (caramelization), which carbohydrates undergo in acid media at elevated temperatures. This topic has been primarily studied in the food industry (Hodge 1953; Ledl and Schleicher 1990; Cui 2005; Lichtenthaler 2011). However, Valchev *et al.* (2020) have also investigated the phenomenon and state that due to the formation of caramelized sugar, the brightness of the MCC from paper grade pulps is drastically lowered at the end of the hydrolysis process. One likely option for the brightness loss is that sulfuric acid reacts with carbohydrates to form pure black carbon after caramelization.

The definition of MCC brightness is “white or almost white” (European Directorate *et al.* 2011). Thus, there is no clear target value of brightness that should be reached. As such, MCC producers often use their own in-house methods to measure color, which makes it challenging to compare different MCC grades from different producers. However, for food and pharmaceutical applications, a high MCC brightness is required. The hydrolysis conditions can be chosen to minimize the brightness reversion, which keeps the brightness at an acceptable level. However, to attain an extremely high MCC brightness (ISO 90%), the hydrolyzed solid residue should be bleached with an oxidative agent, *e.g.*, ozone, oxygen, or peroxide (Vanhatalo and Dahl 2014). These chemicals are normally used for kraft pulp bleaching processes to increase the brightness of the pulp *via* lignin removal or lignin decolorization; however, in this case, the chemicals are used for the removal of caramelized products from the MCC.

The oxidation power of the bleaching chemicals can also be expressed by the oxidation equivalent unit (OXE). The values for different bleaching chemicals are shown in Table 1. However, a high OXE charge is not a guarantee of high brightness. The bleaching process is a complex situation if the operation economy, pulp quality, and environmental aspects are simultaneously considered. However, its usage could be a valuable tool when the design and performance of bleaching sequences are discussed (Grundelius 1993; Chirat *et al.* 2003; Lachenal and Chirat 2005).

Table 1. Conversion Factors to Oxidation Equivalents (OXE)

	Molecular Weight	e ⁻ /mol for Reduction to Cl ⁻ and O ²⁻ , Respectively	g/mol e	OXE/kg
Cl ₂ , (C)	70.91	2	35.46	28.20
ClO ₂ , (D)	67.46	5	13.49*	74.12**
NaClO, (H)	74.45	2	37.22*	26.86**
O ₂ , (O)	32.00	4	8.00	125.00
H ₂ O ₂ , (P)	34.02	2	17.01	58.79
O ₃ , (Z)	48.00	6	8.00	125.00
CH ₃ CO ₃ H(Paa)	76.05	2	38.03	26.30

Note: * 35.46 g active chlorine/mol e⁻; ** 28.20 OXE/kg active chlorine; modified from Grundelius (1993)

To the best of the authors’ knowledge, this is the first extensive study related to MCC bleaching. This work only focused on chlorine-free alternatives, *i.e.*, ozone, peroxide, and peracetic acid (ePaa). This research created a basis for developing the production of high-brightness MCC made with AaltoCell™, using paper pulp as a raw material.

EXPERIMENTAL

Never-dried bleached softwood kraft pulp, supplied from a Scandinavian pulp mill, was used as the cellulose raw material. The degree of polymerization (DP) was 2590, and the ISO brightness (ISO) was 89%. Dilute acid hydrolysis was performed in a 220 L cooking screw under the following conditions: a temperature of 160 to 170 °C and a reaction time of approximately 30 min. The temperature was controlled by steam, and the time adjustment was controlled by changing the screw speed. The hydrolysis agent was H₂SO₄ (93%, CAS 7664-93-9). The acid addition was about 1.2% of the pulp dry content based on the AaltoCell™ method with no mechanical treatment. The short delay is an integral part of the AaltoCell™ process and enables MCC production on a large scale at pulp mills. The AaltoCell™ manufacturing process in the experiments is shown in Fig. 2.

After hydrolysis, the MCC was fully washed using a belt washer. The values of the MCC were as follows: a DP of 320, an average particle size of 23.0 μm (d(0.5)), an ISO brightness of 57%, a pH of 4.1, and a consistency of 34%.

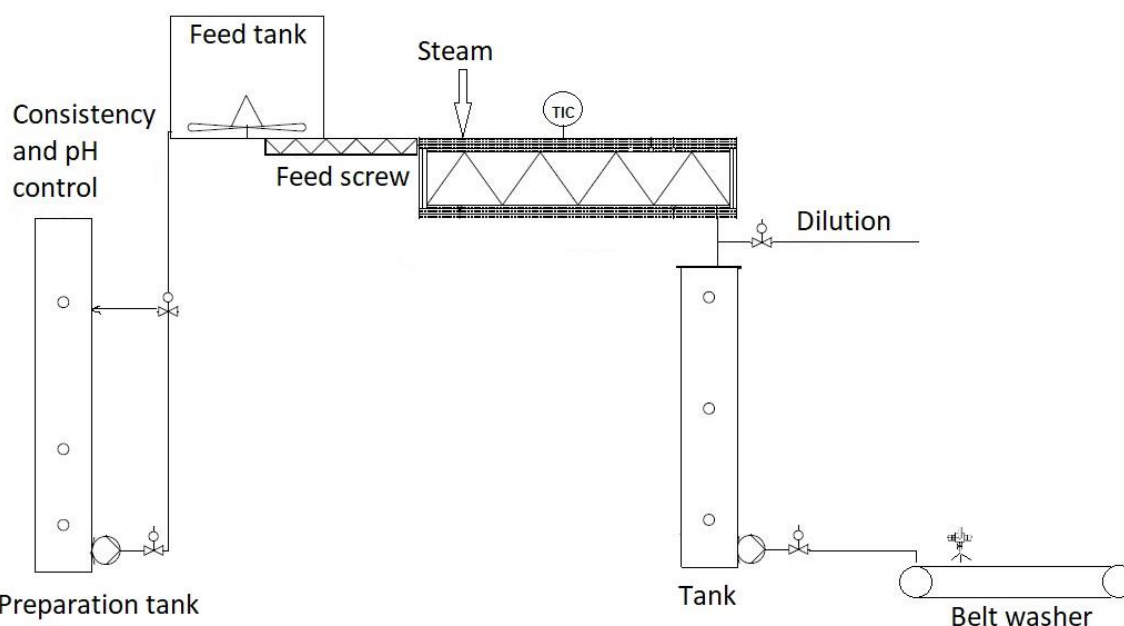


Fig. 2. Schematic diagram of the AaltoCell™ process on the pilot scale

Preparing of the Chemicals

The concentration of the laboratory purchased ePaa used was about 38 to 40%. The ePaa was diluted to 10% for dosing. The concentration of peracetic acid and peroxide in the ePaa was analyzed by titration using the Evonik GmbH method (Author unknown 2020). The dosages were calculated as for the peracetic acid. The hydrogen peroxide used was about 30% laboratory quality. The peroxide was diluted to 10% for dosing. The strength was calculated using following formula,

$$A = \frac{(B * 1.7)}{C} \quad (1)$$

where *A* is the hydrogen peroxide concentration (g/L), *B* is the volume of 0.1N sodium thiosulfate (mL), and *C* is the volume of hydrogen peroxide (mL). The hydrogen peroxide residual was calculated using the following formula,

$$A_{\text{Residual}} (\text{g}) = \frac{(B*1.7*[C*D]-D)}{E*1000} \quad (2)$$

where A is the hydrogen peroxide residual (g), B is the volume of 0.1N sodium thiosulfate, C is the pulp consistency (%), D is the oven dry pulp sample weight (g), and E is the volume of filtrate (mL). The chemicals were dosed per ton of pulp in all cases.

Bleaching Conditions

The bleaching tests were performed using a Quantum Mark IV laboratory mixer (Quantum Technologies Inc., Akron, Ohio). The mixer has a 4.1 L Teflon coated reactor housing and mixer rotor. The mixer has a 7.5 kw motor connected to the rotor shaft by a belt drive. The maximum speed of the mixer is 2400 rpm⁻¹. The reactor housing was surrounded by a heat mantle, where heated rapeseed oil was used to stabilize the temperature. The test equipment also included temperature and pressure measurements as well as data acquisition for the measurements.

A MCC pulp with a 34% consistency was diluted to 13% and added to the kettle. At the same time, an initial pH adjustment was performed with NaOH. The pulp was preheated in a kettle and then poured into the preheated reactor. The chemical dosage of the peroxide or ePaa was added to the reactor, and then the cover of the reaction was closed. The starting temperature in the reaction was approximately 75 °C. The starting pH of 13 was chosen because there was a certain end pH target of about 4.5. According to unpublished results, an end pH of 4.5 is advantageous to get a good bleaching result. The peroxide in the ePaa solution is more active at the beginning of the reaction under alkaline conditions and the peracetic acid again in the acidic range. In practice, peracetic acid is a delignifying bleaching chemical, and its action was directed in the bleaching direction by raising the pH. In this work, it was assumed that lignin was not bleached, but rather any caramelized sugars were bleached. Accordingly, the initial situation was different from that present in a standard pulp mill. The ozone dosing was performed differently, as described later. The bleaching conditions are shown in Table 2.

Table 2. Bleaching Conditions for Microcrystalline Cellulose (MCC) Pulp

	Concentration (%)	Dosage (%)	OXE/ton _{MCC} *	pH Control	pH _{start}	pH _{end}	Sampling (min)
Ozone	10	0.7	875	Drop of H ₂ SO ₄	3.3	3.0	1, 3, and 5
Peroxide	13	1.3	764	1.3 wt% NaOH	13.0	10.5	3, 10, 20, and 40
ePaa	13	1.6	421	0.9 wt% NaOH	13.0	4.5	3, 10, 20, and 40

*Calculated using Table 1 and the chemical dosage per ton of MCC

The pulp was stirred for 15 s at 2400 rpm⁻¹, after which stirring was continued at a slower speed (120 rpm⁻¹) during the reaction. A sampling of the pulp with ePaa and peroxide tests from the reactor over a time schedule (3 min, 10 min, 20 min, and 40 min) was performed using compressed air. Air was vented into the reactor from the valve to obtain a sample from the other valve.

For the ozone bleaching process, the chemical dosage was calculated by the volume

remaining in the reactor and the pressure of the gas fed to it. The amount of pulp in the reactor was calculated using the density of the MCC at a consistency of 10% using a density value of 1000 kg/m^3 . The preparation of the pulp was performed as previously described. In the reactor, the pulp was stirred at 2400 rpm^{-1} for 10 s. During the initial stirring, ozone was fed into the reactor through a valve and then continuously stirred at a slower speed (120 rpm^{-1}) during the reaction. The measurement of the residual ozone was performed by opening a valve from which the remaining pressurized gas was led to the ozone concentration meter. When the reactor pressure was at atmospheric pressure, the reactor cover was opened, and the bleached pulp was recovered for analysis.

The recovered pulp from all test points was filtered through blotting paper ($12 \mu\text{m}$) in a Buchner funnel. The filtrate was collected for further analysis. The pulp was then washed three times (until the filtrate was clear). In the case of the peroxide and ePaa bleaching, the amount of residual chemicals were also titrated from the filtrate. Due to the tablet ISO brightness analysis, the water contained in the pulp was displaced with ethanol for drying, storage, and further processing. The chemical dosages were chosen to achieve a final ISO brightness of approximately 85%.

Analytical Determinations

The samples were analyzed using the following methods: determination of the dry matter content (analytical) according to ISO standard 638 (2021); the chemical oxygen demand (COD) liquor samples were filtrated using $0.45 \mu\text{m}$ paper and then analyzed in a COD analyzer according to ISO standard 15705 (2002); the total organic carbon (TOC) was determined with a total organic carbon analyzer (Shimadzu, Kyoto, Japan) according to ISO standard 8245 (1999); the pH was determined with a Mettler Toledo conductivity meter (Columbus, OH); the ISO brightness (sheet) was determined with an Elrepho analyzer according to ISO standard 2469 (2014); the ISO brightness (tablet) was determined with an Elrepho spectrophotometer, using tablets pressed from powders according to SCAN-P standard 89 (2003); the whiteness (W) was calculated according to ASTM standard E313 (2020), where an object having whiteness of 100% is considered perfect white; the monosaccharide composition was determined *via* high-performance anion-exchange chromatography with pulsed amperometric detection (HPAEC-PAD) after the sulfuric acid hydrolysis (Sluiter *et al.* 2006).

The viscosity was analyzed according to SCAN-CM standard 15 (1999) and then converted to DP according to SCAN-CM standard 15 (1988); and the particle size was determined with a Mastersizer 2000 (Malvern Panalytical, Malvern, United Kingdom) according to ISO standard 13320 (2009).

In addition, the Y-brightness and whiteness were measured from the powder samples using HunterLab's ColorFlex 45/0. The sample was put into a clear glass cup, and the reading was performed though through the bottom of the cup. The Y-brightness is one of the three tristimulus values XYZ of the tristimulus scale. It describes the ability of the sample to reflect green wavelength light, whereas the ISO brightness represents the reflectance of blue wavelength light. The human eye interprets objects as white when they have a blue hue to them. This is why the Y-brightness actually describes the grayness more so than the whiteness of a sample. The Y-brightness was calculated according to ASTM standard E308 (2018) and CIE 15.2 (Carter *et al.* 2018).

RESULTS AND DISCUSSION

Bleaching and Chemical Consumption

The results showed that using peroxide and peracetic acid required additional bleaching time compared to when ozone was used as the bleaching agent (Fig. 3). This was also the assumption before the tests, since ozone is known to be an effective bleaching agent and only requires a few minutes of bleaching when using chemical pulps.

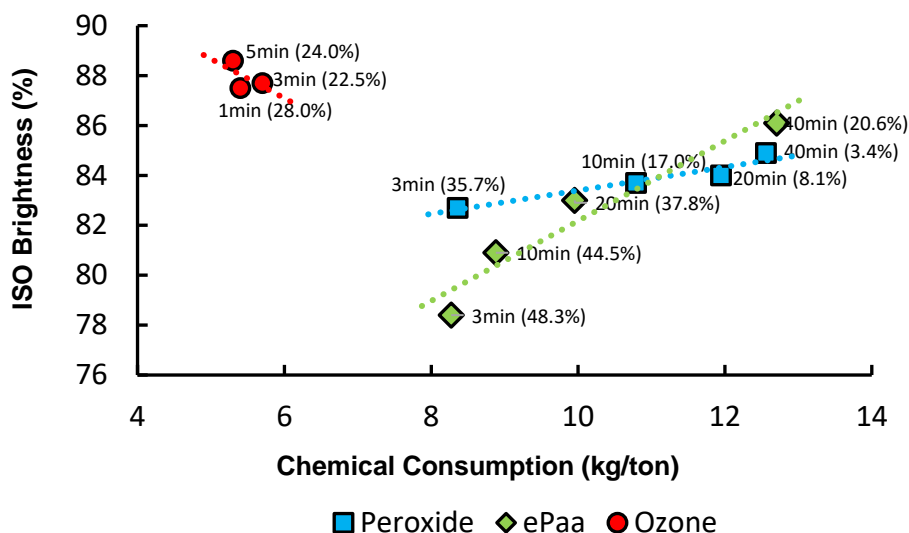


Fig. 3. ISO brightness % as a function of the chemical consumption. Note: the times are bleaching times and percentage in parenthesis is the residual chemical amount; the starting brightness of the raw material was 57.0% ISO units.

Increasing the bleaching time of ozone from 1 min to 5 min only increased the brightness by approximately 1 ISO brightness unit. Therefore, the bleaching effect of ozone is fast and primarily occurs during the first minute. In these tests, it seems that greater than 20% of the introduced ozone was not consumed when a 0.7% dosage was used. Preliminary experiments showed that a dose of 0.6% was too low, yielding an ISO brightness of approximately 84%, but the amount of residual chemicals was lower.

When using peroxide and peracetic acid, the highest brightness values occurred when using the longest bleaching time (40 min). Peracetic acid seemed to increase the brightness more than peroxide. After 20 min, continuation of the bleaching process for another 20 min further increased the brightness by approximately 1 ISO brightness unit for peroxide and by approximately 3 ISO brightness unit for peracetic acid. Therefore, prolonging the bleaching process when utilizing peracetic acid provided greater benefit compared to peroxide. It is possible that the peroxide was also consumed in some other reactions instead of the bleaching process, causing it to decompose during the bleaching process.

The residual amount of peroxide after 40 min was low (approximately 3%), while the residual amount of peracetic acid after 40 min was approximately 20%. It seems that in this study, among the bleaching agent dosages, peroxide was chosen as the most successful considering the low amount of residual chemicals, while peracetic acid requires longer reaction time to attain low residual amount. This work also showed that when

bleaching residues of caramelized hemicelluloses, the increase in brightness is more effective than in bleaching lignin in traditional pulp mills.

Figure 4 shows a comparison of the bleaching agents when the OXE number was used to normalize different chemicals. It should be noted that the OXE number is only a relative measure and shows a comparison purely on a chemical basis. Different bleaching chemicals have different cost levels, and if comparison is made according to this, the results can be totally different.

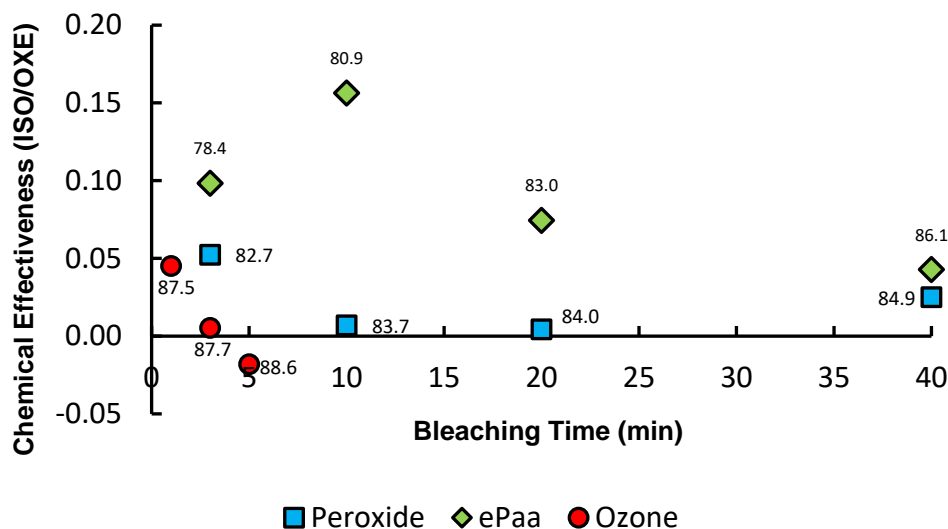


Fig. 4. Chemical effectiveness calculated based on the OXE number as a function of the bleaching time

Peracetic acid is a more effective chemical in terms of bleaching compared to peroxide if the OXE number is used as the comparison basis. After 5 min of bleaching, the effectiveness of peracetic acid almost doubled. After 10 min of bleaching, a majority of the effect of peroxide on the brightness has already occurred and prolonging the process an additional 30 min only yields an increase of 1.2 ISO brightness units, while peracetic acid yields an increase 5.2 of ISO brightness units. This fact is confirmed by the OXE comparison, where peracetic acid is effective during the entire bleaching process at increasing the brightness. As already discussed above, ozone rapidly reacts during the bleaching process, as early as during the first minute. Figure 4 shows this rapid reaction, but at the first measurement point its effectiveness has decreased below the other chemicals.

Filtrate Fractions Analysis

The total dissolved solids concentration (TDS) of the filtrate fraction of the pulp at the reference point, as well as in the case of ozone, were at 0.6 g/L; the TDS of peroxide was 5.0 g/L and the TDS of peracetic acid was 3.5 g/L. The high TDS concentration of peroxide and peracetic acid is due to the addition of NaOH during the pH adjustment. The reducing effect of the NaOH level would have been the same. The reference point COD concentrations were at 670 mg/L and were even lower for the ozone (approximately 550 mg/L). Ozone appears to effectively oxidize all organic matter. However, the concentrations were considerably higher for peroxide (3100 mg/L) and peracetic acid (approximately 6700 mg/L). The TOC concentrations were approximately one-third of the

COD in each case. The high COD and TOC values of peracetic acid, compared to the peroxide filtrates, was attributed to the reaction kinetics of peracetic acid, where acetic acids are formed. In general, the concentrations in the filtrates did not appear to change much as the reaction proceeded for any of the bleaching chemicals used. At least in the case of peracetic acid, further treatment of the filtrate should be undertaken if bleaching is carried out on an industrial level. As such, it should not be directed to a wastewater treatment plant, especially if considerable volumes are utilized.

Table 3. Total Dissolved Solids (TDS), Chemical Oxygen Demand (COD), and Total Organic Carbon (TOC) Analysis Results for the Filtrate Fraction of the Microcrystalline Cellulose (MCC)

	TDS (g/L)	COD (mg/L)	TOC (mg/L)
Reference point, 0-test	0.6	670	200
Ozone	0.6	550	200
Peroxide	5.0	3100	1200
Peracetic acid	3.5	6700	2800

Monosaccharide analysis of the filtrates showed that the hemicellulose contents of the filtrates varied greatly in different bleaching cases (as shown in Fig. 5).

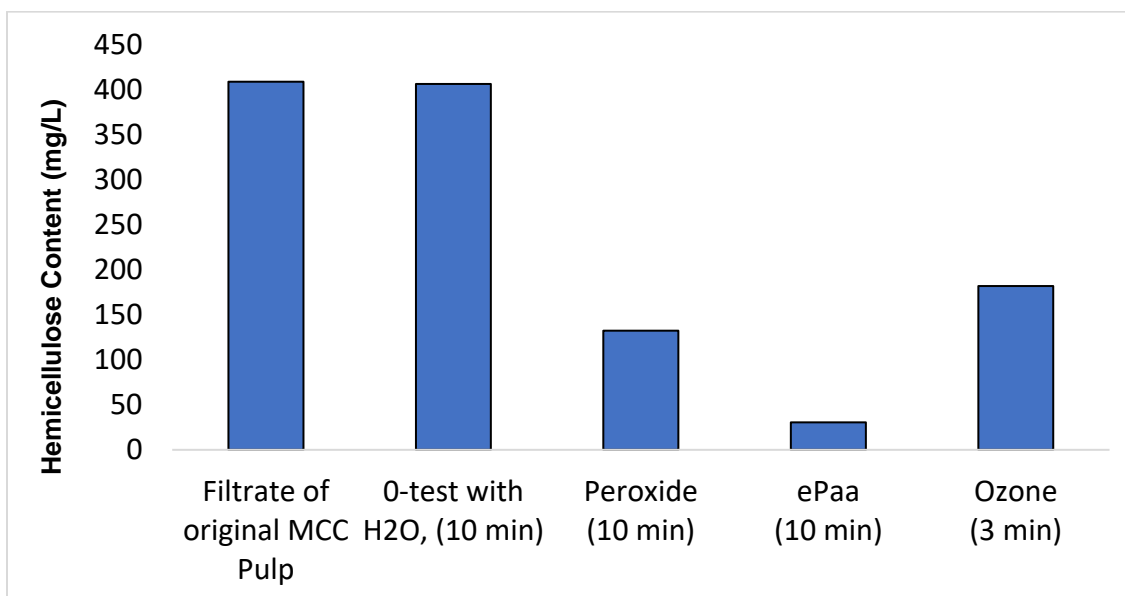


Fig. 5. Amount of monosaccharides in the filtrate samples from the various bleaching stages and original pulp (Note: consistency scaled to 10%)

The filtrate of the diluted original pulp and reference sample (0-test with water) contained approximately 400 mg/L of hemicelluloses. The filtrate of the original pulp is pressed out from the original MCC pulp. The filtrate of the 0-test is the filtrate when the original pulp and water have been mixed for 10 min in a Mark reactor and the filtrate sample extruded from the pulp through wire gauze after sampling. The hemicellulose content is rather low, so that it is difficult to suggest what biochemicals could be made of it, and the potential benefit could be lost if it had to be evaporated. For ozone, the

concentrations were just under half of the reference point; for peroxide and peracetic acid they were less. For peracetic acid, the reaction seemed to consume almost all the hemicellulose. The primary components were xylose, glucose, and mannose (Figs. 6 and Fig. 7).

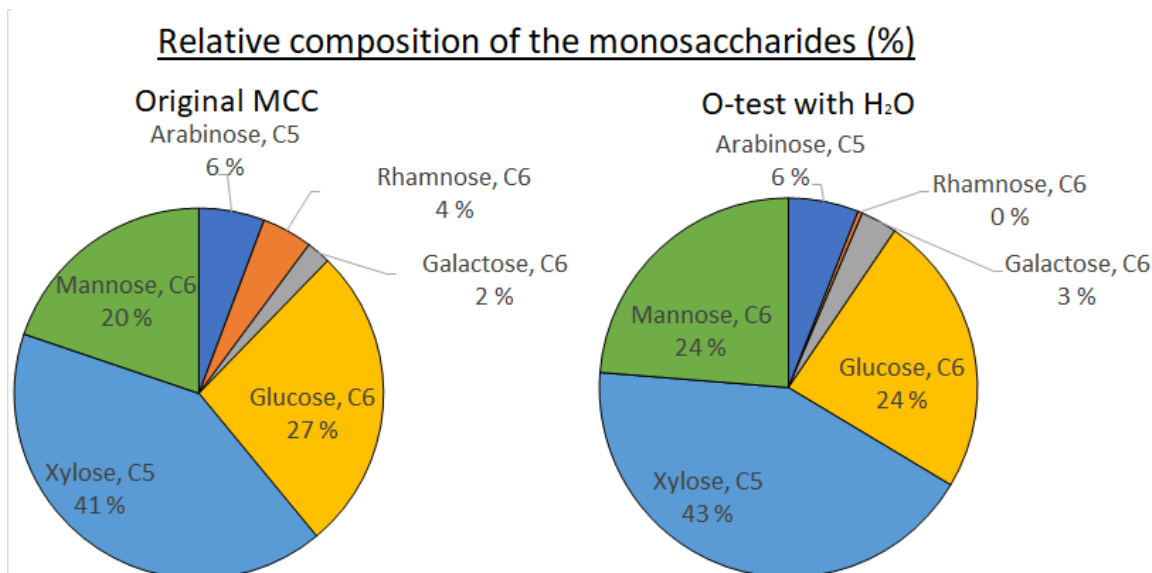


Fig. 6. Relative composition of the monosaccharides in the filtrate of the original MCC and O-test

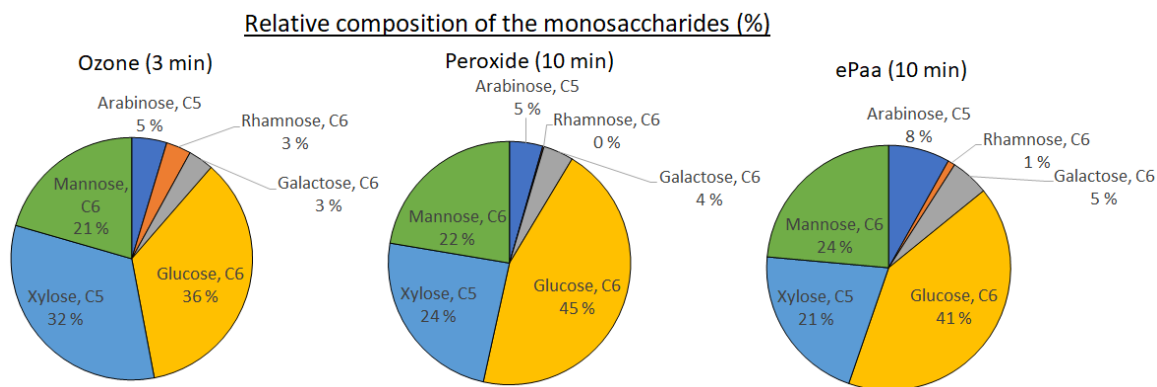


Fig. 7. Relative composition of the monosaccharides in the filtrate samples from the ozone, peroxide, and ePaa bleaching samples after the mentioned reaction times

In addition, arabinose, rhamnose, and galactose were found in the filtrates. The composition of the hemicellulose was similar to the composition obtained by Ristolainen and Alén (1998), where they characterized the composition of the TCF softwood line filtrates at the different bleaching stages. The most common monosaccharide in their study was xylose (40% to 50%), and the composition of the other monosaccharides ranged from approximately 20% to a few percent, with mannose and glucose being the next most common.

Figures 6 and 7 also show how the relative composition of the monosaccharides varied after different bleaching processes versus the filtrates of the original MCC. The relative proportion of xylose (C5) decreased, while the relative proportion of glucose (C6)

increased, in all cases. The proportion of mannose remained fairly constant in all cases, being approximately 20% of the composition. The multitude of oxidative degradation reactions taking place in the pulp during bleaching caused changes in the hemicellulose composition. In other words, aliphatic carboxylic acids were presumably also formed from pulp carbohydrates. This could be one of the reasons for the high COD level of ePaa, but low monosaccharide content.

Comparison of the Different Brightness/Whiteness Measurement Methods

The measured brightness and whiteness values of the different bleached MCC samples are shown in Table 4. The ISO brightness % measured from the sheet was approximately 1 unit to 4 units lower than the corresponding value from the tablet. The sheet was pressed from wet MCC and dried in a condition room, whereas the tablet was pressed from dry powder. Thus, the surfaces of the sheet and tablet are physically different, which has an effect on the ISO brightness. The tablet ISO brightness reached the targeted 85% for almost every test point, excluding the short bleaching time points with peracetic acid and peroxide. Thus, it is possible to reach high brightness in the final MCC powder product with the bleaching chemicals used in this study.

Table 4. Measured Brightness and Whiteness Values of the Different Bleached Microcrystalline Cellulose (MCC) Samples

	ISO Brightness Sheet (%)	ISO Brightness, Tablet (%)	Y-brightness (%)	Whiteness (%)
O ₃ (1 min)	87.5	88.4	93.5	78.9
O ₃ (3 min)	87.7	88.2	93.1	77.2
O ₃ (5 min)	88.6	88.3	95.6	85.9
ePaa (3 min)	78.4	82.1	88.6	65.6
ePaa (10 min)	80.9	83.4	89.9	68.1
ePaa (20 min)	83.0	85.5	91.7	73.4
ePaa (40 min)	86.1	87.5	93.2	77.7
Peroxide (3 min)	82.7	85.6	91.1	70.9
Peroxide (10 min)	83.7	86.8	92.1	74.2
Peroxide (20 min)	84.0	85.9	92.2	74.8
Peroxide (40 min)	84.9	87.0	92.7	76.2

Moreover, Table 4 shows that both the Y-brightness and whiteness increased as the bleaching time increased. Thus, the Y-brightness and whiteness can both be utilized as criteria when the brightness and color of MCC is evaluated. Notably, the whiteness more rapidly decreased from 100% compared to the ISO-brightness and Y-brightness values. For example, the test point for peracetic acid after 40 min had a good ISO brightness of 87.5% and Y-brightness of 93.2%, but the whiteness had dropped to 77.7%.

As mentioned earlier, with the definition of MCC brightness being “white or almost white” and MCC producers having their own in-house methods for analysis, and it is difficult to compare the brightness results obtained here with those of commercial MCC grades. Thus, the tablet ISO brightness, Y-brightness, and whiteness of a few commercial MCCs were analyzed. The obtained values were approximately 80% to 89%, 89% to 95% and 65% to 84%, respectively. These results further showed that the definition of MCC brightness is not particularly strict, and grades with considerably different brightnesses are

manufactured. Hence, the brightness values presented in this study are comparable with those of MCCs available on the market; therefore, bleached AaltoCell™ MCC can compete against them in terms of its brightness.

CONCLUSIONS

1. The selected chlorine-free chemicals, *i.e.*, ozone, peroxide, and peracetic acid, and doses achieved a sufficient ISO brightness value for microcrystalline cellulose (MCC) made *via* the AaltoCell™ process from normal paper pulp. Ozone seems to be the most suitable bleaching agent with a shorter reaction time and the highest brightness values.
2. The results showed that after bleaching with different bleaching agents, the chemical oxygen demand (COD), total organic carbon (TOC), and hemicellulose concentrations in the filtrate fraction greatly varied. This should be taken into account when recovery methods for hemicelluloses or purification methods for filtrates are being planned.
3. The results showed that the definition of MCC brightness is not strict and grades with drastically different brightnesses are manufactured. The target in all cases is to achieve MCCs with a sufficient level of ISO brightness that pleases human eyes.

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