

Partial replacement of chlorine dioxide with ozone in prebleaching of *Acacia mangium* kraft pulp

Md Rezaul Karim, Md Nazrul Islam, and Raimo O Malinen

KEYWORDS: *Acacia mangium*, Hexenuronic acid, Chlorine dioxide, Ozone, Combined use, Pressurized peroxide

SUMMARY: The main objective of this study was to investigate the outcomes from the combined use of chlorine dioxide and ozone in the prebleaching of *Acacia mangium* kraft pulps. Oxygen delignified acacia pulps with two different kappa numbers, ca 12 and 8, were used. In the combined use of chlorine dioxide and ozone, (DZ) mode of application was evaluated at 15-100% replacements of chlorine dioxide with ozone in terms of oxidation equivalent. In this mode of application, 40% replacement gave the best result in terms of kappa reduction, hexenuronic acid removal and brightness gain. At 40% replacement the bleaching sequence (DZ)EopD₁ gave very similar result as reference sequence D₀EopD₁. Brightening with (PO) instead of D₁ in the final stage produced pulp with higher brightness stability, but inferior strength properties.

ADDRESSES OF THE AUTHORS: Md Rezaul

Karim (rezaulkarim68@yahoo.com), Associate Professor, Department of Chemistry, Chittagong University of Engineering and Technology, Chittagong 4349, Bangladesh, **Md Nazrul Islam** (nazrul17@yahoo.com), Associate Professor, Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh, **Raimo O. Malinen** (raimo@ait.ac.th), Visiting Professor, Asian Institute of Technology (AIT), Bangkok, Thailand

Corresponding author: Md Nazrul Islam

(nazrul@cc.tuat.ac.jp) Present address: JSPS Post Doctoral Fellow, Tokyo Univ. of Agriculture and Technology, 3-5-8 Saiwai-cho, Fuchu-shi, Tokyo 183-8509, Japan

Prebleaching operation is considered as the vital part of pulp bleaching. A successful bleaching operation depends on a perfect choice of pre-bleaching stage in many respects. So, the selection of proper chemical and operation mode is important. The banning of the use of elemental chlorine has made chlorine dioxide an essential chemical for pulp bleaching. Chlorine dioxide is being used in pre-bleaching stage as a potential delignifying agent due to its acceptable selectivity to lignin for last decades.

In order to reduce the environmental load, specially the generation of toxic organic chlorinated compounds, efforts have been made to reduce the chlorine dioxide application in bleaching. Many modifications or changes have been studied to reduce the use of chlorine dioxide in prebleaching and as well as in total bleaching. Hardwood kraft pulp contains a substantial amount of hexenuronic acid (HexA) that can contribute 3 to 7 units of kappa number in oxygen delignified pulp (Vuorinen et al. 1999, Ragnar 2001). It is now well known that HexA present in

unbleached pulp consumes bleaching chemicals, such as chlorine dioxide and ozone that results higher bleaching costs and negative environmental impact.

The use of ozone in combination with chlorine dioxide in prebleaching, (DZ) or (ZD) of an ECF bleaching sequence has drawn interest to the researchers in the recent years due to some advantages, such as chemical savings, efficient kappa number reduction, brightness development in preceding stages and reduction of chlorinated organics formation while preserving the strength of bleached pulp (Chirat et al. 1997, Ragauskas et al. 1998, Fisher et al. 1998, Ragnar 2001, Toven et al. 2002). Some researchers (Ragnar 2001, Toven et al. 2002) claimed (DZ) was better than (ZD) in terms of delignification rate and pulp quality. In another study (Karim, Malinen 2007) (DZ) was found advantageous over (ZD) in the case of *Eucalyptus camaldulensis* kraft pulp. (DZ) indicates that chlorine dioxide was charged first and then ozone without washing in between and (ZD) indicates the opposite. Depending on the pulp origin, 1 kg of ozone could substitute for up to 3 kg of chlorine dioxide (Chirat et al. 1997). In the previous study, (DZ) mode of application was investigated for *Eucalyptus camaldulensis*. Malinen et al. (2005) reported that acacia species are different from *Eucalyptus camaldulensis* in pulping and bleaching in many respects, such as fiber morphology, pulping yield, viscosity, HexA content and bleachability. *Acacia mangium* is the main pulp wood species used in fine paper production in Indonesia and is getting more importance in other Asia. In the present work, an investigation was carried out on the combined use of chlorine dioxide and ozone using (DZ) mode of application at different replacements in the prebleaching of *Acacia mangium* kraft pulp.

Experimental

Pulp samples

Industrial chips of *Acacia mangium* were cooked to two different kappa numbers, 20.2 and 14.7 by using a 2.5 liter six-autoclave CRS air heated batch digester. Oxygen delignification was carried out in a CRS 1030 bleaching reactor and kappa numbers after oxygen delignification were 12.1 and 8.2, respectively. Conditions of cooking and oxygen delignification are available elsewhere (Karim 2006). Corresponding viscosities of those two pulp samples were 813 and 680 ml/g, and HexA content were 48.2 and 25.7 meq/kg, respectively. These two pulp samples would be known as high kappa (HK) and low kappa (LK) pulp throughout the content of this paper. Kappa number and viscosity of pulps were determined according to standard SCAN-C 1:77 and SCAN-CM 15:88, respectively. The HexA content of pulp samples was determined according to the method described by Vuorinen et al. (1999). In this method HexA acid groups

are selectively converted to formic acid and furan derivatives. The quantification of HexA groups was done based on the quantification of formed furan derivatives by UV-spectroscopy at 245 nm.

Prebleaching

The prebleaching stages, Z and (DZ) including Eop (oxygen and peroxide reinforced alkaline extraction) were performed in the CRS 1030 bleaching reactor. The D₀ stage was carried out in sealed plastic bags in a thermostatically controlled water bath; conditions are presented in *Table 1*. To obtain the target end pH, probable initial pH was found out by trial and error basis.

In all prebleaching options, the quantities of ClO₂ and O₃ were chosen to maintain identical OXE levels. Kappa factors of 0.23 and 0.25 on the basis of total kappa number were found suitable (Karim 2006) for the HK and LK pulp samples, respectively. By considering these kappa factors as the basis, chlorine dioxide and ozone charges at 15, 25, 40, 50, 60, 75 and 100% replacements were calculated according to the OXE relationship of dif-

Table 1. Conditions of different prebleaching options and extraction

Parameters/ Stages	D	Z	(DZ)	Eop
Temperature (°C)	60	50	50	90
Time (minute)	60	15	D: 30 Z: lnj* + 10	90
Consistency (%)	10	10	10	10
H ₂ SO ₄ (kg/ODt pulp)	2.0 – 6.2	--	--	--
NaOH (kg/ODt pulp)	--	--	--	10
O ₂ pressure (bar)	--	--	--	3.5
H ₂ O ₂ (kg/ODt pulp)	--	--	--	5
MgSO ₄ (kg/ODt pulp)				3
End pH	2.5 – 3.3	2.3 – 3.6	2.6 – 3.8	10.3 – 11.2

* Injection time of ozone

Table 2. Substitution of chlorine dioxide with ozone, their corresponding charges and residuals

Share of O ₃ (%)	Share of O ₂ (%)	ClO ₂ charge* (kg/ODt pulp as active Cl)		O ₃ charge (kg/ODt pulp)		Residual ClO ₂ (kg/ODt pulp as active Cl)		Residual O ₃ (kg/ODt pulp)	
		HK	LK	HK	LK	HK	LK	HK	LK
100	0	27.8	20.5	0	0	2.23	1.62	--	--
90	15	23.6	17.4	0.94	0.69	0.95	1.50	0.00	0.00
75	25	20.8	15.4	1.58	1.16	1.10	1.34	0.15	0.00
60	40	16.7	12.3	2.51	1.85	0.70	0.87	0.10	0.00
50	50	13.9	10.3	3.14	2.31	0.88	0.72	0.14	0.08
40	60	11.1	8.2	3.76	2.77	0.20	0.43	0.23	0.16
25	75	7.0	5.1	4.70	3.47	0.00	0.12	0.40	0.12
0	100	0	0	6.27	4.62	--	--	0.45	0.52

* ClO₂ charge = Kappa number after oxygen delignification × Kappa factor

ferent bleaching chemicals ascribed by Grundelius (1991).

The total OXE was kept unchanged while the proportion of ClO₂ and O₃ were varied. The amount of ClO₂ and O₃ charge at different combination and their corresponding residues after reaction are presented in *Table 2*.

Ozone gas produced by a Trailgaz OZC 1001 generator at a certain flow rate and the concentration calculated amount of ozone for a specific batch was of ozone was measured by iodometric titration method. The volume of zone gas that contained taken into the cylinder of feeding system and then pushed to the reactor by using solid piston compression method. After the completion of reaction, residual ozone in effluent gas was measured. Liquid chlorine dioxide was supplied by a pulp mill in Thailand.

After each batch of D₀ and (DZ) stages pulps were washed with same volume of deionized water. Kappa number and viscosity were determined. HexA kappa was calculated (11.6 meq/kg HexA corresponds to 1 kappa number unit) according to Li and Gellerstedt (1997). The lignin kappa was roughly calculated as the total kappa number subtracted by HexA kappa, because the main kappa number fractions of hardwood kraft pulp is associated with HexA groups and residual lignin (Costa, Colodette 2002). Pulp sheets for measuring ISO brightness were prepared according to SCAN-CM 11:95 standard method and brightness was measured by using the instrument Technidyne Color Touch PC that follows ISO standard 2469.

Final bleaching

The final brightening stage, D₁ of all prebleached pulps was carried out in sealed plastic bags in a thermostatically controlled water bath. The best replacement of chlorine dioxide with ozone in (DZ) mode of application was found out. Pulps, from D₀Eop and (DZ)Eop at best replacement (40%) were also brightened with Q(PO) instead of D₁ in the final stage. Pressurized peroxide stage (PO) was performed in a Teflon coated stainless steel CRS 1065 S Heavy Duty Laboratory Reactor. Conditions of final bleaching stages are shown in *Table 3*.

Chlorine dioxide charge in D₁ and hydrogen peroxide charge in (PO) stage were adjusted to achieve final brightness of 89% ISO. After each batch, end pH, residual chlorine dioxide for D₁ and residual peroxide for (PO) was measured and their consumptions were calculated. Brightness, viscosity and HexA content of each pulp were measured. Aging of all fully bleached pulp sheets were performed according to standard TAPPI T 260 om-85 and reverted brightness was measured. Brightness loss was calculated simply by deducting reverted brightness from final brightness.

Handsheet making and testing of strength properties

All bleached pulps obtained through D₀EopD₁, (DZ)EopD₁, D₀EopQ(PO) and (DZ)EopQ(PO) sequences were used for the testing of strength

properties. All pulps were refined in a PFI mill at 2000, 4000 and 6000 revolutions according to standard SCAN-C 24:27. Laboratory handsheets of 60 g/m² were made according to the standard SCAN-C 25:76 from all unrefined and refined pulps. After drying, handsheets were stored in a conditioned paper testing room for 24 h. Tensile and tear indices were measured by using the standards SCAN-P 11:73 and SCAN-P 38:80, respectively. All tests were duplicated. A schematic flow diagram of experimental set up is presented in Fig 1.

Table 3. Conditions of final bleaching with D₁ and Q(PO) stages

Parameters/Sequences	D ₁	Q(PO)	
		Q	(PO)
Temperature (°C)	70	60	95
Time (min)	180	60	120
Consistency (%)	10	10	10
ClO ₂ charge (kg/ODt pulp as act Cl)	HK / LK: 15	-	-
Residual ClO ₂ (kg/ODt pulp as act Cl)	HK: 0.7, LK: 1.6	-	-
H ₂ O ₂ charge (kg/ODt pulp)	-	-	HK / LK: 12.5
Residual H ₂ O ₂ (kg/ODt pulp)	-	-	HK: 1.0, LK: 1.8
NaOH charge (kg/ODt pulp)	-	-	15
EDTA (kg/ODt pulp)	-	4	-
MgSO ₄ (kg/ODt pulp)	-	-	3
Oxygen pressure (bar)	-	-	6
End pH	3.7 – 4.2	4.8 – 5.3	10.7 – 11.4

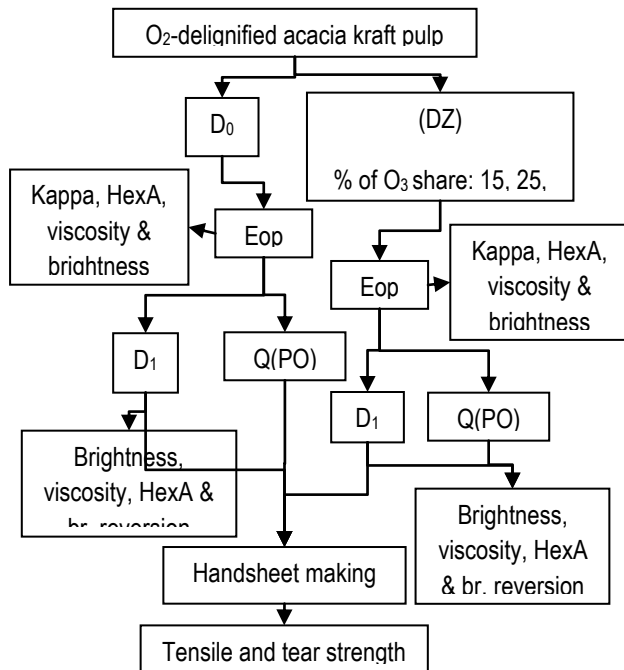


Fig 1. Schematic diagram of experimental set up.

Results and Discussion

Prebleaching With (DZ)

The kappa reduction in prebleaching at different replacements of chlorine dioxide with ozone in (DZ) of both HK and LK acacia pulps are illustrated in Fig 2. The kappa number after Eop stage slightly decreased down upto 40% replacement and after that it was increased gradually upto 100% replacement. This increment was mainly associated with lignin kappa (Fig 3a and 3b). At higher than 40% replacement less lignin was removed as ozone share was increased. A similar result was found by Karim and Malinen (2007) where oxygen-delignified eucalyptus kraft pulp was prebleached with (DZ) stage at different replacement. According to the findings of Ragnar (2001) ozone was less reactive to lignin in comparison with chlorine dioxide.

The influence of ozone in (DZ) was found less efficient in HexA reduction in the case of acacia pulp as shown in Fig 3a and 3b. The amount of HexA was almost unchanged up to 50% replacement and then slightly increased with increasing share of ozone in (DZ) at higher replacements, what was unexpected. This result differs from eucalyptus pulp, where HexA content was decreased down with increasing share of ozone (Karim, Malinen 2007). It may be due to disturbing of other components than lignin and HexA present in the pulp, such as extractives. Acacia species contained considerable amount of extractives than that of eucalyptus (Malinen et al. 2005) which may disturbs in HexA degradation reactions by ozone. Anyway, the results were consistent with both HK and LK pulps, as with eucalyptus (Karim, Malinen 2007). No comparable results on acacia are available in the publications.

Almost similar brightness after Eop stage was maintained upto 50% replacement for both HK and LK pulps; after that decreased significantly as shown in Fig 4. Low brightness at higher replacements can be attributed to higher residual lignin contents. Viscosity also decreased down gradually as replacement of ClO₂ with O₃ was increased in prebleaching.

Ozone is less selective to lignin, but reactive to carbohydrates (which was measured as viscosity) than chlorine dioxide what was reflected at higher replacements.

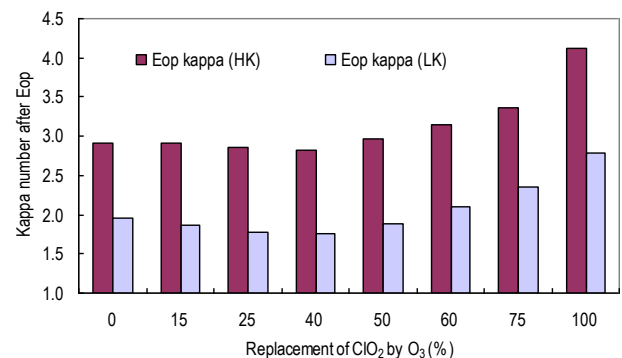


Fig 2. Kappa number after Eop stage of HK and LK pulps at different replacements of chlorine dioxide with ozone in (DZ) stage

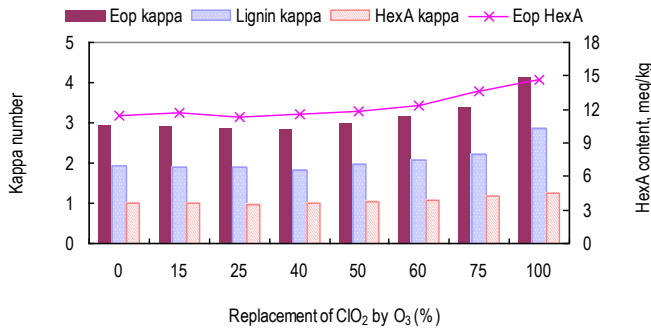


Fig 3a. Contribution of HexA and lignin kappa number to total kappa number after Eop stage of HK acacia pulp at different replacements in (DZ) stage.

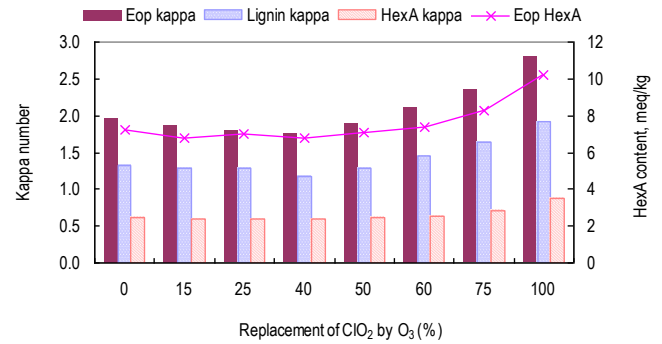


Fig 3b. Contribution of HexA and lignin kappa number to total kappa number after Eop stage of LK acacia pulp at different replacements in (DZ) stage.

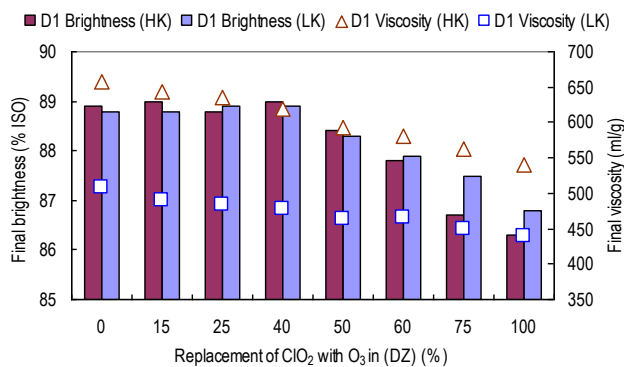


Fig 4. Brightness development and viscosity loss at different replacements of chlorine dioxide with ozone in (DZ) prebleaching

The cause of significant viscosity loss at higher replacements can generally be explained by the fact that ozone produces carbonyl and carboxylic structures within the polysaccharide chains through oxidation reactions; and these groups cause cellulose degradation through chain cleavage upon alkali treatment. Brightness developments in (DZ)Eop prebleaching at different replacements were reflected also in final bleaching. The trend of viscosity loss in prebleaching also was reflected in final bleaching (Fig 5). Fig 5 also shows that the target brightness, 89% ISO was achieved upto 40% replacement for both HK and LK pulps. The LK pulp gave higher brightness compared to HK pulp at higher replacements. At 40% replacement (DZ)EopD₁ resulted similar brightness as was achieved in the D₀EopD₁ with a marginal viscosity loss for both HK and LK pulps.

Replacement of D₁ with (PO) in Final Bleaching

The replacement of chlorine dioxide stage with pressurized hydrogen peroxide in final bleaching was tested for D₀ and (DZ) (at 40% replacement) prebleached pulps; and comparisons were made.

Brightness and viscosity

The brightness-viscosity relationships of both HK and LK pulps finally bleached with D₁ and (PO) are shown in Fig 6. A considerable viscosity loss was observed when pulps were brightened with pressurized peroxide (PO) instead of D₁ while similar final brightness (89% ISO)

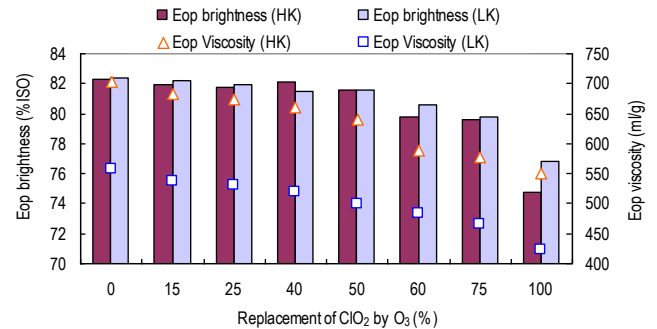


Fig 5. Brightness development and viscosity loss in final bleaching of HK and LK pulps prebleached with (DZ) at different replacements.

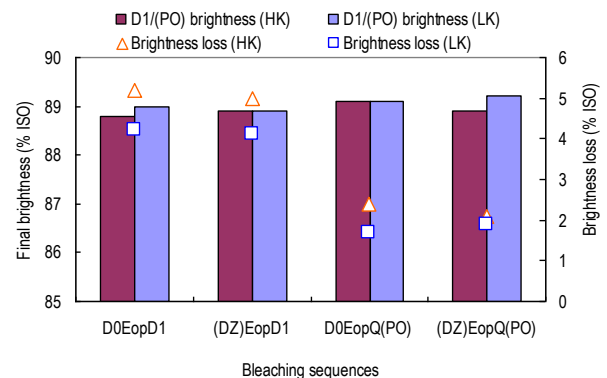


Fig 6. Brightness-viscosity relationship of pulps bleached with D₁ or (PO) in final stage.

was maintained. A similar result was reported by Karim and Malinen (2007) for *Eucalyptus camaldulensis* kraft pulp.

This might have happened due to poor metal management or the swelling of fibers in the alkaline environment. The viscosity difference between HK and LK pulps in cooking was maintained through the final bleaching and the difference was almost constant for both bleaching sequences. Although yield was not measured in this study, it is probable that the LK pulp had a lower total yield compared to HK pulp, as low viscosity is an indirect indicator of yield loss.

Brightness reversion

The impacts of different options in prebleaching and final bleaching on brightness stability are illustrated in *Fig 7*. Pulps, bleached by D_0EopD_1 and $(DZ)EopD_1$ sequences gave very similar results in brightness stability and in the case of both D_0 and (DZ) prebleaching options, (PO) brightening resulted higher brightness stability, i.e., lower brightness loss compared to D_1 brightening. This result was similar as was found with eucalyptus (Karim, Malinen 2007). Also some other studies support this result (Suss et al. 2004, Eiras et al. 2005). It is now known that p-quinoid structures present in bleached pulp are mainly responsible for brightness reversion. Jaaskelainen et al. (2003) reported that chlorine dioxide bleached pulp contains significantly more p-quinoid structures compared to peroxide brightened pulp. Prebleaching with chlorine dioxide leaves p-quinoid structures in the pulp, with a pronounced tendency for brightness reversion. The p-quinoid structures are removed by hydrogen peroxide in alkaline conditions through cleavage reactions. Therefore, brightness stability is significantly improved with a final peroxide stage. On the other hand, the removal of generated quinoid structures is incomplete in final chlorine dioxide bleaching (Gierer 1982). LK pulps possessed higher brightness stability than HK pulp, as found with eucalyptus (Karim, Malinen 2007). This happened probably due to the lesser formation of quinoid structures formed in the prebleaching of LK pulp.

No direct relation between the amount of residual HexA in bleached pulp and brightness reversion was found as shown in *Fig 8*. The placement of (PO) in the last stage of a bleaching option showed lesser brightness loss compared to corresponding sequence contained D_1 . On the other hand, the residual HexA content in (PO) brightened pulp was substantially higher than in D_1 brightened pulp. This result complies with the findings of Malinen and Nhan (2006). HexA is considered as one of the factors cause for brightness reversion, but HexA content alone can not give precise indication about brightness reversion. Some researchers (Tenkanen et al. 2002, Gellerstedt, Dahlman 2003) claimed residual HexA in bleached pulp as the main source of brightness reversion, whereas Suss et al. (2004) found no effect of HexA on brightness reversion. Sevastyanova et al. (2006) reported that brightness loss was found proportional to the content of HexA groups when aging of pulp handsheets was carried out in a sealed plastic bag in a water bath at 70°C for two to nine days. If a bleached pulp contains heavy metals, HexA groups might bind with them and cause brightness reversion (Vuorinen et al. 1999).

Strength properties of bleached pulp

The strength properties of pulps bleached with D_0EopD_1 , $(DZ)EopD_1$, $D_0EopQ(PO)$ and $(DZ)EopQ(PO)$ sequences originated from HK and LK oxygen delignified pulps were evaluated by tear-tensile relationship. For a given pulp sample, almost no negative impact was found on strength properties

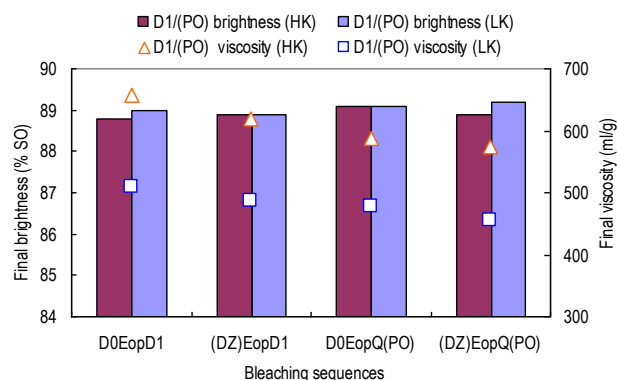


Fig 7. Brightness losses of HK and LK pulps bleached with different options in prebleaching and final bleaching

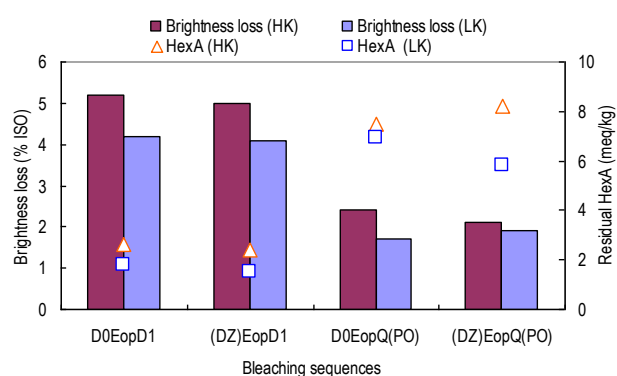


Fig 8. Relationship between brightness loss and HexA content of HK and LK pulps bleached with different options.

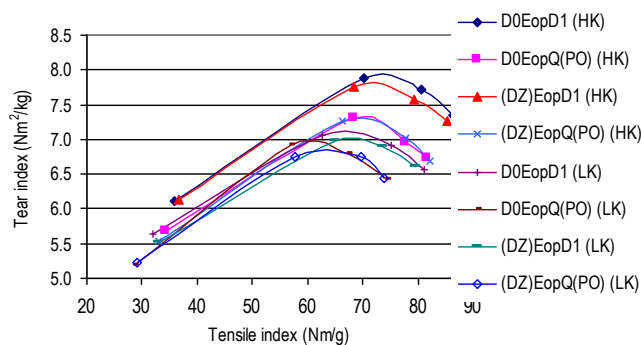


Fig 9. Tear-tensile relationships of HK and LK pulps bleached with different options.

when chlorine dioxide was partially (40%) replaced with ozone in prebleaching (*Fig 9*). The application of (PO) instead of D_1 in final brightening stage showed considerable lower tear strength, especially in the case of high kappa pulp. *Fig 9* also shows a remarkable difference in strength properties between HK and LK pulp samples, which complies with the findings of Malinen and Zhao (2005). This result indicates that cooking to a low kappa number not only reduces the overall yield but also produces pulp with inferior strength.

Conclusions

The suitability of combined use of chlorine dioxide and ozone was studied. The study included also the replacement of chlorine dioxide stage with pressurized peroxide in final brightening. The overall findings of this study can be concluded as follows:

1. Ozone can replace chlorine dioxide up to 40% in prebleaching without negative effects in bleaching in terms of brightness and strength properties. At higher than 40% replacement kappa reduction and brightness development are poor and viscosity loss was considerably high.
2. The introduction of (PO) stage instead of D₁ in the final brightening resulted lower viscosity at similar brightness level. The option (PO) instead of D₁ can be chosen where a reduction of chlorine dioxide use is needed.
3. (PO) brightened pulps showed higher brightness stability compared to the pulps brightened with D₁, although HexA content in (PO) brightened pulp was substantially higher. No relationship was established between residual HexA content in bleached pulp and brightness reversion.
4. Higher kappa gave clearly better strength properties of bleached pulp.

Literature

Chirat, C., Lachenal, D., Angelier, R. and Viardin, M.T. (1997): (DZ) and (ZD) bleaching: fundamentals and application, *J. Pulp Paper Sci.* 23(6), 289.

Costa, M.M. and Colodette, J.L. (2002): The effect of kraft pulp composition on its bleachability. *In: Proceedings of International Pulp Bleaching Conference, Portland, Oregon, USA, TAPPI press*, pp. 195-213.

Eiras, K.M., Francis, R.C., Colodette, J.L. and Lassel, S. (2005): The role of bound chlorine in the brightness reversion of bleached hardwood kraft pulp, *Proc. Intl. Pulp Bleaching Conf., Stockholm*, p.47.

Fisher, S., Corbeil, S. and Sunder, M. (1998): Strength preservation in ozone bleaching using (D/Z) or (Z/D) at low consistency. *In: TAPPI Pulping Conference Proceedings, Montreal, Quebec, Canada, TAPPI Press*, pp. 1429-1444.

Gellerstedt, G., and Dahlman, O. (2003): Recent hypothesis for brightness reversion of hardwood pulps, *Proc. Intl. Colloquium of Eucalyptus Kraft Pulp, Vicoso, MG, Brazil*.

Gierer, J. (1982): The chemistry of delignification. *Holzforschung*, 36 (2):55.

Grundelius, R. (1991): Oxydation equivalents, OXE – an alternative to active chlorine. *In: Proceedings of International Pulp Bleaching Conference, Stockholm, SPCI, Sweden*, pp. 49-58.

Jaaskelainen, A.S., Saariaho, A.M., Matousek, P., Parker, A., Towrie, M., and Vuorinen, T. (2003): Characterization of residual lignin structures by UV Raman spectroscopy and the possibilities of Raman spectroscopy in the visible region with Kerr-gated fluorescence rejection, *Proc. ISWPC*, Madison, WI, p.139.

Karim, M.R. (2006): Use of ozone in ECF bleaching of tropical hardwood kraft pulps. Ph.D. Dissertation, Asian Institute of Technology (AIT), Thailand.

Karim, M.R. and Malinen, R.O. (2007): Suitability of the Combined Use of Chlorine Dioxide and Ozone in Prebleaching of *Eucalyptus camaldulensis* Kraft Pulp, *APPITA J.* 60(3), 228.

Li, J. and Gellerstedt, G. (1997): The contribution to kappa number from hexenuronic acid groups in pulp xylan. *Carbohydr. Res.* 302, 213.

Malinen, R.O., Pisuttipiched, S., Kolehmainen, H. and Kusuma, F.N. (2005): Potential of Acacia species as pulpwood in Thailand. *In: Proceedings of 59th APPITA Annual Conference, Auckland, New Zealand*, pp.443-449.

Malinen, R.O. and Nhan, D.T.T. (2006): Control of hexenuronic acid content in bleached pulp and its effects on optical properties of pulp. *Proc. 60th Appita Ann. Gen. Conf. & Exb., Melbourne*, p.289.

Malinen, R.O. and Zhao, H-P. (2005): Evaluation of the bleachability of *Eucalyptus camaldulensis* kraft pulp. *Proc. Intl. Pulp Bleaching Conf., Stockholm*, p.188.

Ragauskas, A.J., Turner, M., Khandelwal, B., Magnotta, V.L. and Roy, B. (1998): A comparative evaluation of low AOX bleaching sequences. *In: International Pulp Bleaching Conference Proceedings, Helsinki, Finnish Pulp and Paper Research Institute, Finland*.

Ragnar, M. (2001): On the importance of the structural composition of pulp for the selectivity of ozone and chlorine dioxide bleaching. *Nordic Pulp Pap Res. J.* 16(1), 72.

Sevastyanova, O., Li, J. and Gellerstedt, G. (2006): Influence of various oxidizable structures on the brightness stability of fully bleached chemical pulps, *Nordic Pulp Paper Res. J.*, 21(1):49-53.

Suss, H.U., Schmidt K., and Hopt, B. (2004): How to improve brightness stability of ECF bleached softwood and hardwood kraft pulp, *Proc. 58th Appita Ann.Gen. Conf., Australia*, p.493.

Tenkanen, M., Forsskahl, I., Tamminen, T., Ranua, M., Vuorevirta, K., Poppius-Levlin, K. (2002): Heat induced brightness reversion of ECF-light bleached pine kraft pulp. *Proc. of 7th European Workshop on Lignocellulosics and Pulp*. p.107.

Toven, K., Gellerstedt, G., Kleppe, P. And Moe, S. (2002): Use of chlorine dioxide and ozone in combination in prebleaching. *J. Pulp Paper Sci.* 28(9), 305.

Vuorinen, T., Fagerstrom, P., Buchert, J., Tenkanen, M. And Teleman, A. (1999): Selective hydrolysis of hexenuronic acid groups and its application in ECF and TCF bleaching of kraft pulp. *J. Pulp Paper Sci.* 25(5), 155.

Manuscript received February 28, 2011

Accepted May 11, 2011