Laboratory Bleaching System for Oxygen and Ozone Bleaching

Klaus Dölle¹* and Adrian Honig¹

¹Department of Paper and Bioprocess Engineering (PBE), College of Environmental Science and Forestry (ESF), State University of New York (SUNY), One Forestry Drive, Syracuse, NY 13210, USA.

Authors’ contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

ABSTRACT

A multi-functional bleaching equipment for laboratory use was developed. The setup allowed the bleaching of four pulp samples at the same time. The bleaching setup works for traditional oxygen and ozone bleaching, using caustic soda and calcium hydroxides as bleaching additive. This newly developed setup allows creating the tests as flexible as possible, for multiple wood fiber-based pulps. The installation work to change from chemical to gas bleaching can be done in a couple of minutes. The new trial setup showed improvements for the second and third bleaching stage using oxygen and ozone gas. For Kraft pulp using caustic soda as bleaching agent the Kappa number could be reduced by over 97.8%. Calcium hydroxide as bleaching agent resulted in a reduction of 90.0%. Both bleaching agents allowed an increase in L* brightness and tensile index of up to 74.1% and 80.1% respectively for caustic soda and 17.6% and 80.1% respectively for calcium hydroxide as bleaching agent. For straw and coffee filter pulp an increase in L* brightness of up to 58.6% and an increase of the tensile index of up to 67.0% could be achieved without using bleaching agents. Recycled pulp showed an increase in tensile index of up to 71.5% but a decrease of 1% for the L* brightness.
Keywords: Laboratory bleaching system; ozone bleaching; oxygen bleaching; delignification; pulp bleaching.

1. INTRODUCTION

Wood is the major raw material used for producing paper all over the world. The wood fiber is composed of cellulose, hemicellulose, lignin, extractives and ash. The principal constituents of hardwood and softwood are shown in Table 1 by Hübner, Cellulose, hemicellulose and lignin are present in nearly equal amounts. There can be major variances between different wood species. This depends on their consistency and their growing conditions [1].

Table 1. Gross chemical composition of wood [2]

<table>
<thead>
<tr>
<th>Component</th>
<th>Hardwood [%]</th>
<th>Softwood [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose</td>
<td>42-49</td>
<td>41-46</td>
</tr>
<tr>
<td>Hemi-cellulose</td>
<td>23-35</td>
<td>25-32</td>
</tr>
<tr>
<td>Lignin</td>
<td>20-26</td>
<td>26-31</td>
</tr>
<tr>
<td>Extractives</td>
<td>3-8</td>
<td>10-25</td>
</tr>
<tr>
<td>Ash</td>
<td>0.2-0.8</td>
<td>0.2-0.4</td>
</tr>
</tbody>
</table>

Cellulose is a linear polymer made up of glucose units Fig. 1. The degree of polymerization (DP) in wood may reach 10,000. Cellulose molecules are the inner building blocks of a micro-fibril; they can exist in either amorphous or crystalline form. Cellulose is remarkably resistant to acid and alkaline attack [2].

![Fig. 1. Structure of a cellulose molecule as a linear polysaccharide of glucose units [2]](image)

The hemicellulose is a group of branched polysaccharide polymers built of xylan, glucomannan, galactomannan, arabino-galactan and galactan Fig. 2 [2]. The structure of hemicellulose is amorphous. This is the reason why hemicellulose is not as resistant to chemicals attacks as cellulose.

The “glue” of the wood is lignin. Lignin as shown in Fig. 3, is a very complex, highly polymerized, three dimensional network of polymers [4]. The highest concentration of lignin is in the middle lamella. Most of the lignin is found in the cell wall itself. For paper pulp production chemical pulping is a technique to release single undamaged wood fibers from the wood matrix by dissolving lignin from the middle lamella, without or with only a small amount of mechanical force. Depending on the pulping method and the wood species, cellulose fiber extraction from soft wood yields about 60% with a lignin content of approximately 10% of the pulp [2].

![Fig. 2. Structure of hemicellulose molecules [3]](image)

To reach this goal the most common pulping method used today is Kraft pulping. Kraft pulping was first developed by the German scientist Carl Friedrich Dahl in 1879 by substituting sodium sulphate with sodium carbonate, a less expensive material. This allowed replacing the alkali lost in the pulping and chemical recovery process. In 1884 C.F. Dahl obtained US. Patent 229,935 [5,6,7]. Sweden first commercially used Kraft pulp in 1885. From there on Kraft pulping is the most common way of chemical pulping [4]. The name “Kraft” is German and means translated into English “strong”. Kraft pulping produces outstanding strong pulp with very good strength properties. Compared to other pulping methods, the Kraft pulp is darker in color and mostly used for linerboard applications were bright fibers are not required. For other paper applications the whitening and brightening process called bleaching needs to be applied for the production of white fibers.
To produce white fibers the process of bleaching needs to be applied. It is a process in which color originating substances are modified to reduce or lose their light absorption ability or are withdrawn from their functionality. Another aim of bleaching is further reducing contaminations that have not been unhinged, like printing ink or dirt. Chemical pulp, especially pulp made by Kraft cooking is darker in color then the original wood. During the cooking process, the light absorbing properties of residual lignin is increasing. Also cellulose and hemicellulose are gaining some light absorption properties [8]. Before the cooking process native cellulose and most of the other polysaccharides are totally clear [2].

Oxygen bleaching was filed in 1867 Joy and Campbell as a U.S. Patent 663353 for the use of oxygen as a delignification agent [9]. But it took around hundred years from the first steps of using air for bleaching until a viable process became commercialized in 1970. Robert and his team had discovered that the addition of magnesium salt decreased the damage to the polysaccharides during oxygen delignification [10].

The development of oxygen bleaching was promoted by environmental regulations for pulp and paper mills. The industrial application resulted in a decrease of chlorine dioxide use, in particular, the amount of the chlorine dioxide compound in the waste water which has a major negative impact on the environment [11]. Certain benefits of oxygen bleaching are the cost effectiveness and environmental safety compared to chlorine dioxide and hydrogen peroxide bleaching. Further 50-60% of the lignin in Kraft pulp is removed without degrading the cellulose chains [12].
Sodium hydroxide (NaOH), also known as caustic soda, lye or sodium hydrate, is a strong base (pH 13 at 0.1N). Like all other very strong bases, sodium hydroxide reacts with organic materials in a water based solution [13].

Sodium hydroxide is used in pulp and paper production, textiles’ finishing, bleach manufacturing, petroleum products, aluminum production, and various chemical processing [14]. A major property of NaOH is the function to swell up cellulose fibres and to enable other chemicals to enter or modify their texture [15]. Another chemical additive that can be used for oxygen bleaching is calcium hydroxide [16,17]. Calcium hydroxide has a low solubility in water [18]. Further, the solubility decreases as temperature increase. Calcium hydroxide scales on heated surfaces. The scaling is caused by the low solubility of calcium hydroxide. In addition, deposit formation also increases by using calcium hydroxide [19].

A limitation is that oxygen has a lower reactivity and selectivity compared to the common bleaching agents like chlorine.

In the early seventies the paper research centers started trials to replace oxygen with ozone. Ozone molecules are stronger oxidants than oxygen and are very reactive and react with most organic substances including ligno-cellulose. After the usage ozone is decaying to oxygen molecules again. Ozone helps also disinfecting the pulp which is a strong benefit for hygiene paper like washroom or kitchen papers or papers used in medical environments [1].

Ozone is toxic. The maximum allowed daily 8-hours exposure is 0.1 ppm [2]. Ozone is a strong electrophile which reacts with functional groups in residual lignin. Most phenolic groups are oxidized by ozone. Ozone acts better than chlorine and chlorine dioxide to solubilize lignin. Ozone is also far more reactive towards than carbohydrates like polysaccharide (cellulosics and hemicellulosins). But during the reaction from oxygen to ozone, byproducts emerge, which are acting as radicals that are very reactive with carbohydrates [2]. Carbohydrate degradation stems the formation of carbonyl and carboxyl structure on the polysaccharide chains. With strong reducing agents as borohydride the ozonated pulp can be reduced. The use of ozone in delignification would dramatically increase if a reducing agent could be developed which is more cost effective [2].

The main process conditions for ozone bleaching are: Consistency, time and temperature, and chemical additives.

Ozone bleaching increases the brightness and the tensile index and decreases the lignin content in the fibre walls. This helps to prevent the yellowing of produced paper [20].

To investigate new bleaching applications in a laboratory setting it is necessary to develop a bleaching laboratory setup which allows to research various bleaching methods safely on a small scale, is easy to use and affordable in regard to operation and installation cost.

The objective of this research was the design and testing of a multi-use laboratory bleaching setup for different kinds of pulps. The laboratory setup should allow bleaching trials for gas bleeding with oxygen (O₂) called (O-Stage) and ozone (O₃) called (Z-Stage), including the use of sodium hydroxide (NaOH) and calcium hydroxide (Ca(OH)₂) as bleaching additive. The bleaching setup should operate without the usage of high pressure devices at an operating pressure below 1 bar. To observe basic laboratory safety rules, the bleaching setup should fit in a standard chemical laboratory hood size (1500 mm length x 1000 mm x depth x 2000 mm height). Further it was desired to bleach separate samples at the same time. All the sample reaction vessels should be transparent to get an idea what is happening inside the vessel during the bleaching process. Further the handling of the reaction vessels including set-up and troubleshooting should be simple.

2. BLEACHING SYSTEM SETUP

Fig. 4 shows the experimental set-up for gas bleaching. For bleaching with Oxygen (O₂), O₂ is flowing through the switched off (O₃) generator located between the O₂ pressure tank and the bleaching vessel. For O₃ bleaching the O₃ generator is switched on to produce O₃ gas. Identical flasks are used as reaction vessels for the O and Z bleaching stage. Rubber stoppers are used to seal the reaction vessels. Sodium hydroxide bleaching works best under higher temperatures therefore, a temperature-controlled water bath is used. Gas bleaching with oxygen and ozone does not require high temperatures. A shaker plate or individual stirring hot plates with temperature control can be used. The rubber stoppers contained two lines, which allowed the gas to enter and to exit.
Installation of the test design and switching to different bleaching operations can be done in less than an hour.

After constructing and initial testing of the trial setup, different pulp samples were tested as described in the following material section.

3. MATERIALS AND METHODS

3.1 Paper Fiber Materials

Materials used for the experimental bleaching setup in Fig. 4 were:

- First, unbleached hardwood Kraft pulp prepared to the procedure outlined in [22];
- second, hardwood Kraft pulp bleached with sodium hydroxide and calcium hydroxide prepared to the procedure outlined in [23];
- third, recycled pulp produced at a paper mill using waste paper from street collection;
- fourth, unbleached coffee-filter pulp supplied by a paper mill; and fifth, straw paper pulp produced from straw art paper sheets.

3.2 TAPPI Testing Methods Used

Handsheets for physical testing were prepared accordance with T 205 sp-06 [24]. The basis weight of the handsheets produced was 125g/m² requiring 2.5 g OD of fiber material. This allowed the production of handsheets with a constant fiber distribution. Handsheets were cut in samples according to TAPPI T 220 sp-10 [25]. Kappa number of the recycled pulp was measured in accordance with T 236 om-06 [26]. Conditioning of the paper samples was done according to T 402 sp-08 [27]. Tensile strength properties were examined according to TAPPI T 404 cm-92 [28].

The tensile strength for calculation of the Tensile Index (TI) was measured with a tensile tester, made by “Testing Machines INC (tm), Amityvill, N.Y., U.S.A.”, model No. 84-21. Basis weight of the samples was measured according to TAPPI T412 [29]. Moisture content of pulp was determined by T412 om-06 [30]. Brightness of pulp was measured according to T 452 om-08, [31].

The brightness of the manufactured 2.5 g handsheets was measured with a spectrophotometer type “Technidyne – Color Touch 2 Model ISO”, by Testing Machines INC (tm), Amityvill, N.Y., U.S.A.

3.3 Oxygen Bleaching

The oxygen bleaching in a laboratory scale is usually done in a pressure vessel. To start bleaching gas is added into the reaction vessel with the pulp slurry mixing with the chemical reactant. After the reaction time of about 60 minutes, the pressure relief valve is opened and the sample becomes washed and dewatered [22, 23].

The bleaching system used for this research as described above is different. The bleaching is performed under a temperature of 24°C. A small amount of O₂ gas is constantly added at a preset pressure of 68.9 kPa into the reaction flasks. The advantages are a very constant mixing and dispersion of the fibers.

A consistency of 1% was defined in preliminary trials to achieve the best results using a 1000 ml flask as reaction vessel. It is necessary to strive for a very low consistency to reach a good and
constant intermixing and good exposure of the fibers to the injected \( O_2 \) or \( O_3 \) gas. 10 g of OD fibers had been determined to be required for the analyses of one Kappa numbers and make two hand sheets for paper testing and a small amount of buffer for washing or potential errors during the analyses. A pressure of 10 psi was set at the pressure regulator of the oxygen tank to ensure a constant flow out of the air dispenser stones on the bottom of the bleaching vessels. For \( O_3 \) bleaching the \( O_3 \) generator located between the \( O_2 \) pressure tank and the bleaching vessel was switched on to produce \( O_3 \) gas.

3.4 Ozone Bleaching

The bleaching conditions for the ozone trials were kept the same as for the oxygen bleaching as described above. Here it is important to collect the gas outlet after its contact with the pulp and capture it in a flask with potassium iodide (KI) solution. The KI is a strong oxidant and reacts with ozone \([20]\). It gives the proof that ozone was actually active and bubbled through the pulp samples. Trial two and four were done using an ozone generator: “GRIFFIN TECHNICS” New Jersey. Trial six was done with another ozone generator by “PCI-WDECO” Model GL-1, due to a technical problem with the first generator.

3.5 Experimental Design

The experimental design for unbleached Hardwood Kraft pulp Fig. 5, Recycling Pulp Fig. 6, Coffee Filter and Straw Pulp Fig. 7, allows a comparison of the influence between ozone bleaching and oxygen bleaching. For all stages sampling and bleaching conditions were kept as identical as possible.

The process for the two stage bleaching model using hardwood Kraft pulp shown in Fig. 5 included washing of the pulp, followed by dewatering and then separately bleaching with either sodium hydroxide (NaOH) or calcium hydroxide (Ca(OH)\(_2\)). The pulp was then finally washed, screened and dewatered, then bleached in the second stage with either oxygen (\( O_2 \)) or ozone (\( O_3 \)), followed by finally washed and dewatered.

![Fig. 5. Hardwood Kraft pulp](image)

![Fig. 6. Recycling pulp](image)
4. RESULTS

Fig. 8 shows that the first bleaching stage with Ca(OH)$_2$ caused a significant change for all the pulp properties. The Kappa number dropped 77.59% from its initial 64.91 points to 14.55 points and the brightness increases by 61.85% from its initial value of 51.80 to 83.84.

The tensile index dropped about 10.75% which accords to 2.21 points from its initial number of 20.56 Nm/g to 18.35 Nm/g. Oxygen bleaching with Ca(OH)$_2$ in the second stage reduced the Kappa number by 38.97% from 14.55 to 8.88. The brightness was decreasing by 0.94 or 1.12% from 83.84 to 82.90. An increase for the Tensile Index (TI) was achieved by 30.35% from 18.35 Nm/g to 23.92 Nm/g.

Ozone bleaching with Ca(OH)$_2$ in the second stage resulted in a decrease for the Kappa number by 55.26% or 14.55 points to 6.00 Nm/g. L$^*$ Brightness increased by 5.10% or 4.28 points from 83.84 to 88.12. The tensile index improved by 31.83% or 3.63 Nm/g from 18.35 Nm/g to 24.19 Nm/g. This is 3.63 Nm/g or 17.66% higher than the unbleached Kraft pulp and 6.00 Nm/g 31.83% higher than the Kraft pulp bleached with Ca(OH)$_2$.

Fig. 9 shows a two stages bleaching using NaOH as additive for the first bleaching stage. In the second bleaching stage oxygen or ozone are applied as reactive gas. The first bleaching stage causes a significant 90.54% drop of Kappa number from 64.91 to 6.14 and a L$^*$ brightness increases of 62.86% by 32.56 points from 51.80 to 84.36. The tensile index is increasing 19.45% by 3.00 Nm/g from 20.56 Nm/g to 24.56 Nm/g. The oxygen trial as the second stage caused nearly no changes for the kappa number and brightness. The Kappa number decreased by 1.95% or 0.12 points from 6.14 to 6.02. The L$^*$ brightness decreased by 0.42% or 0.36 points from 84.36 to 84.00. The tensile index is increasing 38.43% or 11.44 Nm/g points from 24.56 Nm/g to 34.00 Nm/g. Oxygen bleaching for the second stage resulted in a decrease of the Kappa number by 76.38% or 4.69 from 6.14 to 1.45. The L$^*$ brightness increased by 7.36% or 6.5 points from 84.00 to 90.18. The tensile index increased 50.81% or 12.48 Nm/g from 24.56 Nm/g to 37.04 Nm/g.
Fig. 10 shows a different effect during bleaching of the kraft pulp with Ca(OH)$_2$ and NaOH. The hand sheets made of NaOH bleached pulp are far stronger than the bleached samples made out of Ca(OH)$_2$ pulp. The tensile index (TI) of Ca(OH)$_2$ bleached pulp decreased 10.75% or 2.21 points from 20.56 to 18.35. The pulp which was bleached with NaOH was increasing its TI 19.46%, 4.00 points from 20.56 up to 24.56 points. The pulp which was bleached with Ca(OH)$_2$ in first stage became bleached with oxygen respectively ozone as a second stage. The TI was raising 30.35% to a level of 23.92 after oxygen bleaching which is almost identical to 24.19 after ozone bleaching, which gave 31.83%. These results are t 25.29% (6.21 points) higher compared to the level of 18.45 after Ca(OH)$_2$ bleaching. The NaOH bleached pulp has increased its TI with NaOH bleaching 19.46% from 20.56 to 24.56, exactly 4.00 points. After bleaching with oxygen the TI was increasing further 38.44% (9.44 points) up to 34.00 points. The highest TI was obtained by NaOH bleaching in combination with a second stage of ozone bleaching. The NaOH and ozone bleached pulp was improving its IT 50.81% (16.45 points) up to 37.04 points. The difference between the bleaching sequences of Ca(OH)$_2$ +O$_3$ and NaOH+O$_3$ are about 53.12% and 12.85 points.

The NaOH bleached pulp causes the better results after ozone bleaching compared to the Ca(OH)$_2$ bleached pulp. The NaOH pulp after its first stage has bleached 2.33% (1.06 points) brighter, the kappa number was 57.80%
Dölle and Honig; AJOCS, 4(2): 1-12, 2018; Article no.AJOC5.40620

(8.41 points) lower and the tensile index was 34.69% (6.21 points) stronger than the Ca(OH)$_2$ bleached pulp. The Kappa number difference after ozone bleaching both samples is 77.73% (5.06 points). The brightness difference of the Ca(OH)$_2$ bleached pulp after the ozone stage is 2.06 points (2.28%) less than after NaOH bleaching. The difference of the tensile index is 34.69% (12.88 points) after ozone bleaching both pulps.

4.1 Bleaching Recycling Paper

The recycling paper trial was planned to show differences between flotated and unflotated paper pulp. The Kappa for the recycled paper pulp could not be established due to inconsistencies in the pulp supply. The recycling paper trial focused only on changes for the brightness and tensile index.

As shown in Fig. 11, the brightness hasn’t changed positively for the whole recycled paper test. At the start point an initial $L^*$ brightness number of 67.47 is shown and even the floated and ozon bleached pulp has only reached 66.80 and dropped about 0.67 points which corresponds to 0.99%.

The tensile index is improving after the flotation and is further improving with all gas bleaching trials. The floated pulp itself caused a 71.45% or 14.29 Nm/g increase in the tensile index to 34.29 Nm/g. The unflotated pulp increased after oxygen bleaching 53.85% or 10.77 Nm/g to 30.77 Nm/g. Ozone bleaching resulted in a 60.95% or 14.19 Nm/g increase to 34.19 Nm/g.

The results for the tensile index for pulp sample that had been flotated before oxygen and ozone bleaching are lower but still apparent. Oxygen bleaching resulted in a 2.89% or 1.01 Nm/g to 35.28 Nm/g increase. Ozone bleaching improved the floated pulp by 9.51% or 3.26 Nm/g to 37.55 Nm/g. The flotation step followed by bleaching improved the recycled pulp by a total of 87.75% or 17.55 Nm/g to 37.55 Nm/g.

4.2 Straw Paper Trial

For the straw paper trial is was not possible to create matching kappa numbers. The reason are the harder cell walls of the unmodified straw used for the straw paper and therefore, neither for the oxygen nor the ozone run was it possible to separate lignin molecules out of the straw fibers as shown in Fig. 12.

The $L^*$ brightness of the unbleached straw pulp of 72.01 was improving during the oxygen bleaching stage by 0.46% or 0.34 points to 72.34. Ozone bleaching resulted in a 5.46% or 3.94 points of brightness improvement to 75.94. The difference between the brightness after oxygen and ozone bleaching is 5.00% or 3.60 points.

Oxygen and ozone bleaching improved the tensile index from its initial 10.32 Nm/g by 66.96% or 8.38 Nm/g to 17.23 Nm/g for oxygen bleaching. Ozone bleaching resulted in a 87.60% increase or 9.02 Nm/g to 19.36 Nm/g. The tensile index difference between oxygen and ozone was 2.13 Nm/g points or 21.36%.

![Fig. 11. Recycling pulp, flotated and unflotated bleached with O$_2$ and O$_3$](image-url)
4.3 Kraft Pulp Unbleached

Fig. 13 shows that the Kappa number of the Kraft cooked hard wood sample was decreasing by 3.22% during oxygen bleaching from an initial Kappa number of 64.91 by 2.09 points to 62.82. Ozone bleaching resulted in a Kappa number decrease of 15.04% or 9.76 points to 55.15. The difference of the Kappa number between the oxygen and ozone bleached sample was 12.21% or 7.67 points.

The L* brightness of the unbleached hardwood pulp of 51.80 was improving during the oxygen bleaching stage by 14.27% or 7.39 points to 59.19. Ozone bleaching resulted in a 26.03% or 13.48 points brightness improvement to 65.28. The difference between the brightness after oxygen and ozone bleaching is 11.76% or 6.09 points.

Oxygen and ozone bleaching improved the tensile index from its initial 25.81 Nm/g by 32.47% or 8.38 Nm/g to 34.19 Nm/g for oxygen bleaching. Ozone bleaching resulted in a 73.89% increase or 19.07 Nm/g to 44.88 Nm/g. The tensile index difference between oxygen and ozone was 10.71 Nm/g points or 41.42%.

4.4 Coffee Filter Pulp

Handsheets made from initial coffee filter pulp, and oxygen and ozone bleached coffee filter pulp in Fig. 14 shows that the coffee filter pulp improved its brightness during the oxygen and ozone bleaching. Testing data in Fig. 14 from the oxygen and ozone bleaching test using the new bleaching system shows that the initial Kappa number for the coffee filter pulp very low at 3.27. Oxygen bleaching decreased the Kappa number by 18.04% or 0.59 points to 2.68.
Ozone bleaching was able to decrease to Kappa number by 75.23% or 2.46 points to 0.81. The difference between oxygen and ozone bleaching for this experiment is 57.19% or 1.87 points.

The initial brightness number of 86.30 was improved during the oxygen bleaching by 0.15% or 0.13 points to 86.43. The ozone bleaching improved the brightness by 5.86% or 5.04 points to 91.34. The brightness difference between oxygen and ozone is 5.71% or 4.91 points.

Oxygen and ozone bleaching improved the tensile index from its initial 12.35 Nm/g by 36.28% or 4.48Nm/g to 16.83 Nm/g for oxygen bleaching. Ozone bleaching resulted in a 71.90% increase or 8.88Nm/g to 21.23 Nm/g. The tensile index difference between oxygen and ozone was 4.40 Nm/g points or 25.62%.

5. CONCLUSION

This research project demonstrated that the developed laboratory bleaching procedure is suitable to bleach paper pulp at 1% consistency using a chemical bleaching agent such as NaOH and Ca(OH)₂ with and without O₂ and/or O₃ as a bleaching gas. The setup of the procedure allows the change between different bleaching setups in a couple of minutes. A switch to O₃ bleaching can be done by just turning on the ozone generator. Using one 1000 ml beaker flasks allows bleaching 10 g OD pulp at 1% consistency. Using 4 1000 ml flasks allows bleaching enough pulp for the analyses of Kappa number and/or mechanical and/or physical handsheet properties. Using a set-up of 4 flasks allows the produce redundant samples for analyses. The new trial setup showed improvements for the second and third bleaching stage using oxygen and ozone respectively. For Kraft pulp using caustic soda as bleaching agent the Kappa number could be reduced by over 97.8%. Calcium hydroxide as bleaching agent resulted in a reduction of 90.0%. Both bleaching agents allowed an increase in L* brightness and tensile index of up to 74.1% and 80.1% respectively for caustic soda and 17.6% and 80.1% respectively for calcium hydroxide as bleaching agent. For straw and coffee filter pulp an increase in L* brightness of up to 5.86% and increase in tensile index of up to 67.0% could be achieved without using bleaching agents. Recycled pulp showed an increase in tensile index of up to 71.5% but a decrease of 1% for the L* brightness.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here: http://prh.sdiarticle3.com/review-history/24144