Delignification, Yield, Defibreability, and Brightness of Pine Wood (*Pinus sylvestris*) Pulped Using the Alkaline Sulphite Method with the Addition of DDA and Ethylene Glycol

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Sodium sulfite (Na_2SO_3) is known as a selective chemical agent for wood delignification. In this work, Scots pine (*Pinus sylvestris*) wood was pulped using alkaline sulfite (AS) with the addition of 1,4-dihydro-9,10-dihydroxy anthracene (DDA) [called also soluble anthraquinone (SAQ)] and ethylene glycol (G). The studies showed the possibility of obtaining Kappa number (KN) 24 to 26 alkaline sulphite-DDA pine pulps with total and screened yields higher by 3.4 to 3.9% and 1.4 to 2.6%, respectively, than in the case of kraft pulping. The AS-SAQ pulping process was also characterized by much higher brightness of pulps but worse defibreability of wood than the kraft process. Increasing the amount of Na_2SO_3 dosed to the wood from 25% to 30-35% (based on wood) and adding G to the cooking liquor increased the delignification of pine wood in the AS-SAQ method to Kappa number of 17 to 20 units (without G) and approximately 14.5 units (with G). Such a modification had a positive effect on the defibreability of wood after pulping and the brightness of pulps but a negative effect on the screened yield of AS-SAQ and AS-SAQG pulps.

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Keywords: Pine wood; Alkaline sulphite pulping; DDA, Degree of pulping; Total yield; Screened yield; Reject content in digesters pulp; Brightness

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INTRODUCTION

Sodium sulfite (Na_2SO_3) is one of the most selective wood delignifying agents. However, due to its mild action on wood, it is currently commonly used only for the production of semi-chemical neutral sulfite pulps (NSSC) from hardwood. For this reason, several researchers have undertaken the development of a method aimed at using Na_2SO_3 for processing wood into pulps with a higher degree of delignification and even intended for bleaching (Ingruber and Allardo 1973; Kettunen *et al*. 1979; Virkola *et al*. 1981; MacLeod and Fleming 1983; McDonough *et al*. 1985; MacLoed 1987). This is how the alkaline sulfite (AS) method was developed. This method involves the pulping of wood in a Na_2SO_3 solution with the addition of NaOH to obtain a pH of 10.0 to 13.5 for cold cooking liquor and 8.0 to 9.5 for hot liquor (Ingruber and Allard 1973; Kettunen *et al*. 1979; Virkola *et al*. 1981). The AS method sparked the attention of papermaking technologists also due to the known disadvantages of industrial methods of chemical production of fibrous papermaking pulps (the wastewater disposal in calcium base sulfite

mills, the odor nuisance of kraft pulp mills, and the low yield of pulp obtained from pine wood) (Palenius 1979; MacLoed 2007).

The first work on the use of the AS method to produce fibrous chemical papermaking pulps showed that in the case of the wood of coniferous trees (pine, spruce), this method is characterized by a much slower course in term of delignification in comparison to the pulping of wood in the kraft pulping process (sulphate method) (Ingruber and Allardo 1973). A breakthrough in AS method was the discovery of the possibility of significantly shortening the pulping process of this kind of wood, *e.g.*, to even 40 min and 3 h at 175 ºC and obtaining high-yield linerboard grade pulps (Stradal 1985) or even regular papermaking pulps with a Kappa number (KN) of 30 units, respectively, as a result of adding a small amount of anthraquinone (AQ) to the cooking liquor (AS-AQ process) (Kuttunen *et al*. 1979; MacLoed and Fleming 1983).

The AS-AQ method has been modified several times. For example, this has been done by adding sodium sulfide (Dahlbom *et al*. 1990), methanol (ASAM process) (Patt and Kordsachia 1986; Abdallah *et al.* 2023), and ethanol (ASAE process) (Usta *et al*. 1999). This increased the delignification of wood in the AS process, but it was associated with the introduction of an odor-inducing delignification agent to the delignification system and the need to protect the installation against the explosion of alcohol vapors and their harmful effects on people. These problems effectively blocked the possibility of applying for example of the ASAM process in industrial practice (Wandelt 1992).

Another type of modification of the AS-AQ method that can be considered is the replacement of powder AQ with soluble 1,4-dihydro-9,10-dihydroxy anthracene (DDA). This agent had previously been shown to be useful in accelerating the delignification of wood in kraft (Furuya 1984; Dutta and Biermann 1989), soda (Wandelt 1979; Wandelt and Surewicz 1983; Silva Junior and Barrichelo 1995), semichemical (Kubes *et al*. 1995), and chemimechanical pulpings (Imada *et al*. 1987), but not in the case of the AS process. Further work on AS-AQ method has addressed the determination of the pulping effects of poplar wood (Kordsachia *et al.* 2008); varying concentrations of pulping chemicals on the delignification and polysaccharide retention in pulps (Paananen *et al.* 2015); and the effects of AS-AQ pulping of spruce wood with addition of $NaBH_4$ (Erişir *et al.* 2015). It can also be stated that, apart from one experiment from McDonough *et al*. (1985), most works on the pulping of pine wood using the AS method have used a large share of NaOH in the Na_2SO_3/NaOH ratio, which, however, may have a negative impact on the yield of the pulps and their brightness.

Several attempts to use the AS-AQ method to process non-wood raw materials into fibrous papermaking pulps were also made (Hedjazi *et al.* 2008; Sahab *et al.* 2008; Hedjazi *et al.* 2009; Dutt *et al.* 2010; Jahan Latibari *et al.* 2011; Moradbak *et al.* 2016).

The present work, unlike most of the studies done so far, focused on the specific effects of pulping Scots pine (*Pinus sylvestris*) wood using the AS method modified by adding 1,4-dihydro-9,10-dihydroxy anthracene (*i.e.*, DDA, also known as soluble anthraquinone, or in short SAQ; Dutta and Biermann 1989) and ethylene glycol (G) to the pulping liquor (AS-SAQ and AS-SAQG variants). This type of wood was selected because it is the mass raw material for papermaking in the temperate climate zone and the most difficult kind of wood to pulp chemically. DDA, unlike powder AQ, was used in this work in the form of a liquid rather than a powder. Such an approach makes it easier to distribute the additive evenly in the cooking liquor, thus improving the efficiency of the catalytic action of this catalyst. Meanwhile, ethylene glycol was used because it is not as explosive as methanol and ethanol (Wandelt 1992), has a high boiling point, and it is easily available.

Moreover, a relatively low share of NaOH in the ratio of pulping chemicals (*i.e.*, Na_2SO_3 : NaOH), *i.e.*, 83 to 90% : 10 to 17%, was used in experiments in which the pH of the cooking liquid did not exceed 12 units, to check how it will affect the pulp yield and brightness.

The research was performed in the form of a comparative evaluation of (1) the extent of pine wood delignification in the AS-SAQ, AS-SAQG, and kraft pulping, (2) the total yield (TY) and screened yield (SY) of the pulps obtained using these methods, (3) the defibreability of pine wood chips after their pulping, and (4) the brightness of the pulps. One additional experiment of pine wood pulping was also carried out using the alkaline sulphite method (AS) in order to demonstrate the effect of action of sodium sulphite with addition of a small amount of NaOH on this kind of wood without any additives.

EXPERIMENTAL

Fibrous Raw Material

The research used industrial wood chips of Scots pine (*Pinus sylvestris*) obtained from a Polish pulp mill. These chips were screened in a laboratory Santasalo-Sohlberg shaker-type sorter equipped with sorting plates with a diameter of 6 to 36 mm. In the research, chips collected from plates with a diameter of holes of 13, 16, and 19 mm were used. These chips were additionally subjected to manual sorting by removing defective pieces (*i.e.*, containing knot wood and bark) and those that were too thick (*i.e.*, thicker than 4 mm).

Chemicals

The following chemicals were used in the study: sodium sulphite, sodium hydroxide, and ethylene glycol purchased from POCH Company (Poland) as a pure for analytic purpose grade substance. The DDA solution containing 14.5 g of this component and 6 g of NaOH/L prepared by dilution of an original 18% DDA solution were supplied by Mitsubishi Corp.

Alkaline Sulphite Pulping without (AS) and with the Addition of DDA (AS-SAQ) and Ethylene Glycol (AS-SAQG)

The pulping experiments using the alkaline sulphite (AS) method were conducted under the following conditions: 15 min initial steaming of the chips with hot steam; the amount of Na_2SO_3 dosed was 30% based on oven-dried (o.d.) wood as NaOH; the amount of NaOH dosed was 4% based on o.d. wood.; liquid module was 4. The heating time to a maximum temperature was 120 min, and the pulping time at a maximum temperature of 175 °C was 150 min. The second (AS-SAQ) and third (AS-SAQG) variants of the AS method of pine wood pulping in this work were performed under the same conditions (amount of NaOH, temperature, and time) as mentioned above for the AS method. These variants differed from the AS pulping experiments in the addition of an alkaline solution of DDA (1,4-dihydro-9,10-dihydroxy anthracene) to the cooking liquor in the amount of 0.2% based on o.d. wood and the addition of ethylene glycol (G) in the case of the AS-SAQG pulping experiments in the amount of 80% based on o.d. wood (with maintaining the liquid-wood module at the level of 4:1). In both variants, the amount of NaOH dosed in the pulping process (*i.e.*, 4%) was reduced by the small amount of this chemical dosed together with DDA.

Apart from this, the variable condition in the AS-SAQ and AS-SAQG variants of AS method was the amount of N_2SO_3 dosed based on o.d. wood. These amounts are presented in Table 1.

Table 1. Amount of Na_2SO_3 Dosed in the AS-AQ and AS-SAQG Pulping Experiments (chemicals dosed in % based on o.d. wood)

AS-SAQ Pulping			
-	25	30	35
AS-SAQG Pulping			
20	25	30	35

The initial cold pH of cooking liquor used in all experiments was between 11.7 and 11.9 units. All pulping experiments were performed in triplicate using a laboratory digester from Santasalo-Sohlberg Oy Company (Finland) in 320 cm^3 steel autoclaves heated with hot air.

Comparative Kraft Pulping of Pine Wood

These experiments were carried out to obtain the results of pulp yield, pulp degree of fiberization after pulping, and delignification level (KN) from kraft pulping using the same batch of pine wood as in the AS methods, prepared for testing in the same way. The amount of wood, steaming of chips, liquor-to-wood ratio, the heating time to a temperature of pulping, kind of digester, and the number of repetitions of the pulping process were the same as in the case of AS pulping. The factors that distinguished these experiments from this method were the pulping chemicals: a mixture of NaOH and Na_2S solutions dosed as active alkali (a.a.) in amounts of 19, 21, and 23% based on o.d. wood (as NaOH) and the sulphidity of chemicals of 25%, process temperature: 172 °C, and pulping time of 120 min.

Processing of Pulped Wood After Pulping

After pulping, the pulped wood was initially washed with water on a sieve, then it was diffusion-washed for 24 h in distilled water. Next it was defibered in a laboratory propeller mixer at a propeller rotation speed of 1000 rpm and dried to determine the total yield (TY). This value is known also as digester pulp yield or brutto pulp yield (*i.e.*, pulp with unfibered wood). The pulps were then defibered in water to obtain suspension of fibres and screened in a Weverk sorter equipped with a sorting screen with a slot width of 0.2 mm. The uncooked parts of wood separated from the pulps were dried and weighed to determine their percentage content in the digester pulp (*i.e.*, the R index) and to calculate the screened yield index (SY).

Oxygen Delignification (OD) of Kraft Pulp

A weighed amount of KN 29.1 pine kraft pulp pre-defibered in water and drained (dryness of approximately 25%) was placed in a plastic bag, and then the following substances were added to it successively: 0.02% magnesium sulphate ($MgSO_4$) based on 100% dry pulp (b.o.p.) in the form of a 2% solution, and an appropriate amount of sodium hydroxide (NaOH) solution (in these studies 2.5 or 3.0% b.o.p.). The contents of the bag were then mixed by kneading and then transferred to the interior of the autoclave of the Jayme rotary digester. The autoclave was closed with a lid and filled with oxygen to 8 MPa. The rotary mechanism was turned on, and its contents were heated to the process temperature of 100 °C for 30 min. Then, heating was continued at this target process

temperature. After the OD process time had elapsed, the autoclave was degassed and emptied, while pulp was drained on cheesecloth, washed twice using 500 mL of distilled water, drained, and stored in a polyethylene bag.

Determination of Kappa Number (KN) and Brightness of Pulps

The KN and brightness of the sample pulps ($R_{457\ nm}$) were determined in accordance with the PN-70/P-50095 (1985) and ISO 1240 (1999) standards, respectively. The SpectroColor 01 apparatus from SpectroColor Company (Poland) was used to determine the first of these features.

RESULTS AND DISCUSSION

Figure 1 presents the results of determining the KN of pine pulp samples obtained from the AS method (only one point), from the AS method with additives (AS-SAQ and AS-SAQG variants), and from kraft pulping.

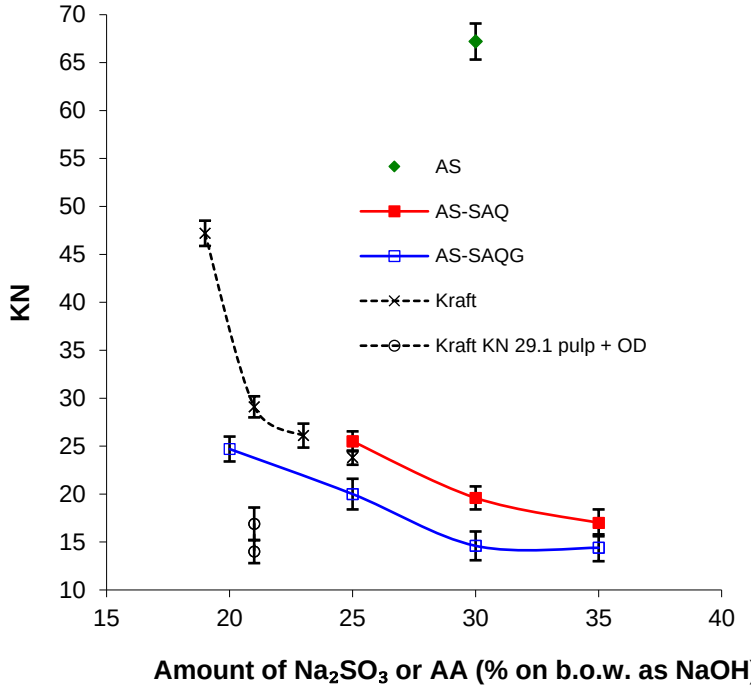

Fig. 1. KN of pine pulp samples obtained by the AS method, AS method with additives (AS-SAQ and AS-SAQG), and from kraft pulping

These data show that from the point of view of production pulps intended for bleaching, the AS method without the addition of AQ was of little use. With 30% of Na_2SO_3 and 4% NaOH dosed to the dry wood, high-yield cardboard pulp with a KN of 67.2 units was obtained using this method. Similar effects were observed by other authors when using it with coniferous wood, although they were obtained with different total amounts of active alkali and proportions of Na_2SO_3 and NaOH to wood, *e.g.*, 12 : 9 to 14% (Ingruber and Allard 1973), 10.4 : 14.0 (MacLoed and Fleming 1983) (all % of chemicals based on o.d. wood) or using methods other than AS but showing many similarities to it,

e.g., neutral sulphite anthraquinone one (NS-AQ) (McDonough *et al*. 1985; Wandelt 1990; Hanhikoski *et al*. 2016).

The AS method took on a completely different meaning with the addition of AQ to the cooking liquor. Figure 1 shows that in such a case (AS-SAQ variant) from pine wood pulps with KN of 17.0 to 25.5 units can be obtained even using only 4% NaOH based on o.d. wood. The obtained level of pine wood delignification using the AS-SAQ method can be considered surprisingly good, because it leads to obtaining pulps characterizing the delignification level of regular papermaking pulps and easily-bleachable pulps when 25% and 30 to 35% of Na_2SO_3, respectively, is used in the pulping process based on o.d. wood. This is why one can risk the statement that in terms of delignification efficiency it can compete with different modified kraft processes. A comparison of AS-SAQ pulp with KN of 25.5 units with pulps from laboratory kraft pulping experiments of pine chips showed that this sample in terms of delignification level corresponds to the kraft pulp sample obtained in laboratory conditions using ~23% of a.a. based on o.d. wood, while the AS-SAQ pulp sample with KN of 17 corresponded to oxygen delignified kraft pulp with an initial KN of 29.1 (Fig. 1, sample: kraft KN 29.1 + OD) obtained using ~21% a.a. based on o.d. wood in pulping and 2.5% NaOH based on o.d. pulp in the OD process.

The obtained results can only be compared to those of MacDonough *et al*. (1985), who in one experiment pulped southern pine wood using the AS-AQ method with a liquor containing Na_2SO_3, NaOH, and AQ in the amounts of 19.2%, 4.8%, and 0.1% based on o.d. wood, respectively, obtaining, however, worse delignification effects, *i.e.*, KN of pulps about of 55 units. This was similar to other pulping experiments in which the authors used twice as much NaOH or combination of Na_2CO_3 and NaOH as the alkalizing substances. The relatively high KN in these experiments could have been caused by both the difference in the wood species and the use of AQ by these authors, probably in the form of powder, which can limit delignification in pulping process (Wandelt 1990).

As already mentioned, the effect of replacing 1/5 of water in the cooking liquor with ethylene glycol on the results of pulping pine wood by the AS-SAQ method was also investigated. The relationship between KN and the amount of Na_2SO_3 dosed in the AS-SAQG process (Fig. 1) shows that such a modification further deepens the delignification of pine wood by this method. At the dosing of 25 and 30% Na_2SO_3, the KN of the AS-SAQG pulp decreases from 25.5 and 20.0 units to 19.6 and 14.6 units, respectively, in the latter case, reaching the level of pulping of pine kraft pulp with KN of 29.1 delignified with oxygen with the use of 3% of NaOH based on o.d. pulp. Progress of delignification of pine wood pulp by the AS-SAQG method with the use of 35% Na_2SO_3 based on o.d. wood (reduction of this number by only another 0.2 units in comparison to 30% of Na_2SO_3 used based on o.d. wood) indicates that delignification has already reached the level of content of lignin moieties in the pulp in which this biopolymer consists mainly of condensed moieties (Henriksson *et al*. 2024). Similarly good effects of delignification of pine wood by the AS-AQ method in terms of obtaining pulps intended for bleaching were also achieved only by Paananen *et al*. (2015).

Pulp yield is an important factor in the economic evaluation of pulping processes. Figure 2 shows the effect of the tested AS pulping process variants on the TY and SY. It also presents results of determination of the content of uncooked wood parts in the digester pulp (R index) used in this work to compare the defibreability of pine wood subjected to pulping using different methods.

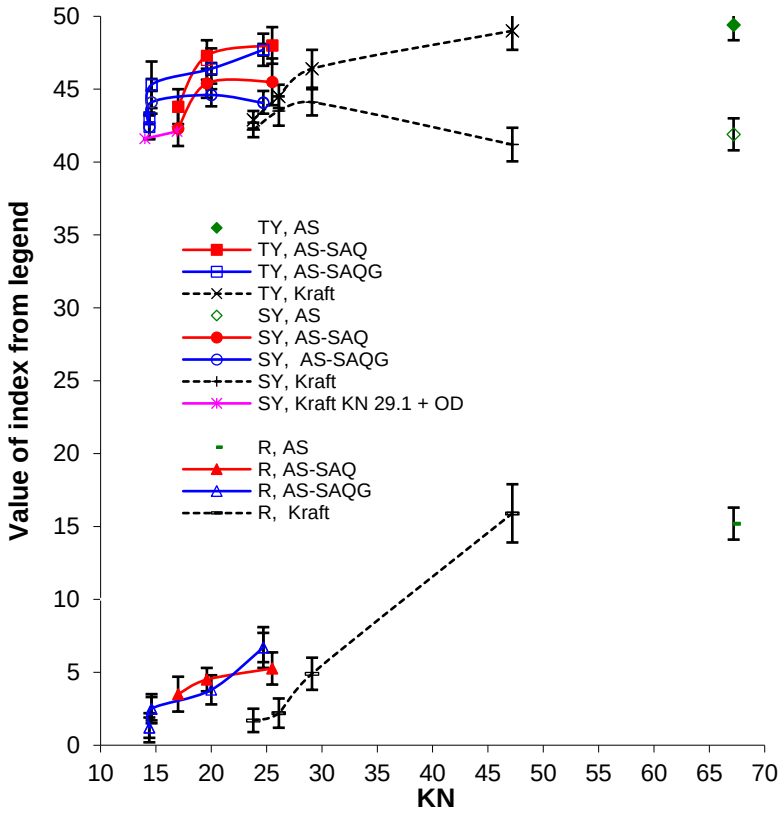

Fig. 2. TY and SY, and percentage content of undefibred wood in digester pulp (rejects - R) of pulp samples obtained by pulping of pine wood using AS, AS-SAQ, AS-SAQG methods, and in kraft pulping process. Results of TY and SY are presented as % based on o.d. wood, while R as % based on o.d. pulp

Figure 2 shows that TY and SY values (TY/SY) (in this work the writing symbol / was used instead of the word "and") of AS-SAQ pine pulps in the KN range of pulp approximately 20 to 25 were at the levels of approximately 47.7%/45.5%, while for pulps obtained by the AS-SAQG method they are at the levels of approximately 47.1%/44.4%. The first of these four values is comparable to the pulp yield values obtained by Paanenen *et al*. (2015) for the pulping of Scots pine grown in Finland by the AS-SAQ method using 3% of AQ based on o.d. wood. The authors do not provide information on how this form of AQ was obtained. It is known that, in addition to DDA, an AQ solution can also be obtained by preparing the so-called Fieser solution made from powdered AQ, NaOH, $Na_2S_2O_4$, and water (Vogel 1984). The TY and SY yields of AS-SAQG pulps from pine wood with such a degree of pulping were therefore lower than those of AS-SAQ pulps by approx. 0.6 to 1.1%.

The results presented in Fig. 2 show also that after exceeding the KN of pulps of 20 units, the selectivity of pine wood delignification by the AS-SAQ method decreased. This is evidenced by the values of TY/SY yield of AS-SAQ pine pulp samples with a KN of 17 units, which were 43.8%/42.3%, respectively. A similar phenomenon can be observed in the case of AS-SAQG pulp samples after the lignin content in them reached a level corresponding to KN 14 to 15 units, whose TY/SY yields were in the range of 43.0 to 45.3%/42.4 to 44.1%, *i.e.*, on average 44.2%/43.3%, respectively.

A comparison of the average TY and SY values of AS-SAQ and AS-SAQG pulps with these yields of kraft pulps at the KN level of 24 to 26 units shows that the former were higher than the latter by 3.4 to 3.9% and 1.4 to 2.6%, which indicates a higher selectivity of pine wood delignification using the AS-SAQ(G) methods than in kraft pulping process up to this KN level. However, the advantage of AS pulps over kraft pulps decreases as delignification moves to the level of deeply delignified pulps. For example, by stopping the delignification of kraft pulp at the level of 29.1 KN units and continuing it to KN 14-17 using the OD process, which is considered more selective in the final stage of pulp delignification (Parsad *et al.* 1994; McCubbin 1997), a similar level of pulp SY yield can be achieved as in the case of AS–SAQ and AS-SAQG at the same level of delignification. So, at such level of delignification of pine wood using the AS-SAQ and AS-SAQG methods, despite the reduced amount of NaOH, the effect of higher wood pulp yield is not achieved as observed in the case of the KN 25-26 level, as well as in comparative studies of the NS-AQ and kraft pulping processes (Kettunen *et al*. 1979).

As already mentioned, the data presented in Fig. 2 also enable the evaluation of the defibreability of pine wood pulped using the AS-AQ and AS-SAQG methods and the comparison of this feature of these pulps with its values obtained in kraft pulping. The issue of defibreability of wood in the pulping process is conveniently considered by comparing the content of uncooked wood parts in pulp coming out for the digester, *i.e.* so-called "rejects". When discussing this feature of pulped wood, it is assumed in pulping technology that after pulping it is well defibered when the pulp obtained as a result of its defibering contains, by convention, less than 5% of these parts (Mróz and Surewicz 1981). It should be noted that the results of the evaluation of this feature of pulping processes presented below concern laboratory conditions. In industrial conditions, when wet chips of about 50% moisture content are subjected to pulping and industrial methods of impregnating these chips with cooking liquor are used, together with modern pulping techniques, the values of this index may be lower. For example, Westin *et al.* (2002), for the of birch wood form kraft pulping in a modern installation using Lo-Solids technique, reports the content of uncooked parts of the wood in the digester pulp from this installation as 0.8%.

The data in Fig. 2 indicate that the defibreability of pine wood subjected to AS pulping using 30% Na_2SO_3 based on o.d. wood was low (about 84.8% of wood came into the form of fibers). For AS-SAQ and AS-SAQG methods, these two methods gave similar results, and at the same time at the KN 25 level was worse than the defibreability of this wood in kraft pulping (approximately 95% of wood transformed into pulp *vs.* 98%, respectively). However, the defibreability of pine wood subjected to AS-SAQ and AS-SAQG pulping improved to 96.5% and even 98.8%, respectively, with a decrease in the KN of the pulp due to the increasing amount of Na_2SO_3 dosed to the wood and adding ethylene glycol to the cooking liquor. The obtained results therefore provide a good perspective for obtaining in the industry high defibreability of pine wood pulped using the AS-SAQ method.

Figure 3 shows the brightness of AS-SAQ and AS-SAQG pulps and kraft pulps.

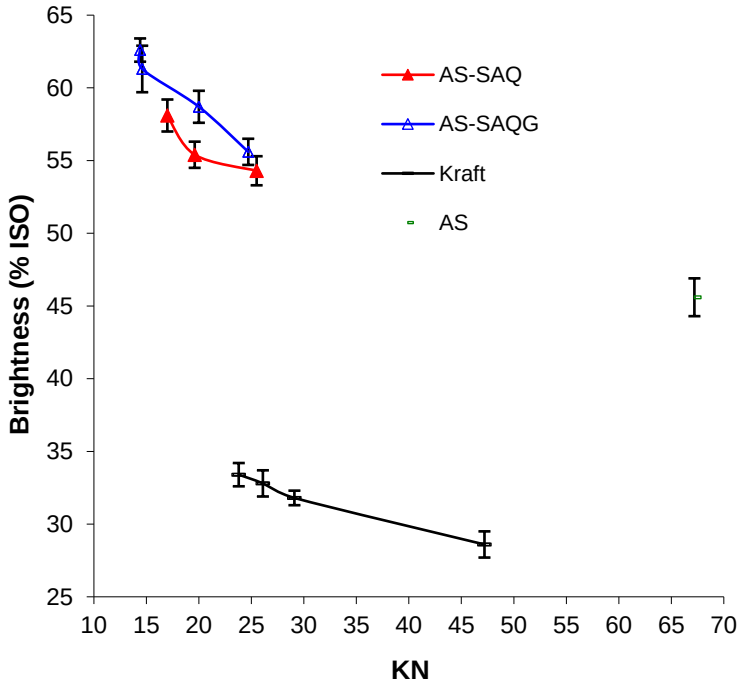

Fig. 3. ISO brightness of AS, AS-SAQ, and AS-SAQG and kraft pulps at different levels of their KN

The figure shows that AS-SAQ and AS-SAQG pulps with a KN of 25.0, 17.0, and 14.5 units were characterized by a brightness of 54.5% to 55.5%, 58%, and 61%, respectively. They were higher than the feature of unbleached and oxygen delignified kraft pulps with such KN by approximately 23.0 to 24.5%. The considerably higher brightness of AS-SAQ and AS-SAQG pulps can be regarded as an advantageous feature because of its positive effect on the susceptibility of pulps to bleaching. It results from high share of Na_2SO_3 and the low share alkalizing agent in the mixture of pulping chemicals, as indicated by the results of previous authors' works (Kettunen *et al*. 1979; McLoed *et al*. 1983; McDonough *et al*. 1985; Hanhikoski *et al*. 2016).

CONCLUSIONS

1. Studies show that the alkaline sulfite – soluble anthraquinone (AS−SAQ) pulping of pine wood with the use of 25 to 35% Na_2SO_3, 4% of NaOH, and 0.2% of DDA (all chemicals based on o.d. wood) proceeded much faster than without the addition of DDA. After 3 h of pulping this wood at 175 ºC with a chip thickness of no more than 4 mm, pulps with a Kappa number of approximately 17 to 26 units were obtained, *i.e.*, characterized by regular and extended pulping delignification. The delignification of such wood can be further extended to a Kappa number of 14 to 20 units by adding 80% ethylene glycol based on o.d. wood as a second additive to the cooking liquor (AS-SAQG pulping). Considering the requirement of glycol regeneration in industrial practice, questions arise regarding the rationale for its application when introducing the AS-SAQ method in this context, although such

installations for separating methanol from black liquor from wood pulping using the ASAM method operated on a semi-technical scale in Germany.

2. During delignification of pine wood using AS-SAQ/AS-SAQG methods to Kappa number 20 to 25 pulps, the total yield and screened yield (TY/SY) of such pulps was approximately 47.7%/47.1% and approximately 45.5%/44.4%, respectively. However, if the delignification in the digester of pine wood was carried out to Kappa number from 17 and 14 units using these methods, the TY/SY of AS-SAQ/AS-SAQG pulps decreased to 43.8%/42.3%, and 44.2/43.3%, respectively. At this low level of delignification, the screened yield of AS-SAQ and AS-SAQG pulps is comparable to the yield of oxygen-delignified pine kraft pulp with KN 29.1 after pulping.
3. The results indicate that wood of *Pinus sylvestris* delignified by the AS-SAQ method may require slightly more extended delignification than in kraft pulping to achieve pulping point required for regular kraft pulps in laboratory tests, *i.e.*, the content of uncooked parts of wood in the digester pulp (R index) less than 5% (KN 22 units instead of 29 units as in the case of the later process). The addition of ethylene glycol to the digester liquor did not significantly affect the defibreability of pine wood in AS-SAQ pulping.
4. The brightness of the AS-SAQ and AS-SAQG pulps obtained in this study was in the range of 54 to 62%, and at a level of KN 14.5 to 25 units this feature of pulps was higher than the one of the unbleached and oxygen-delignified pine kraft pulp by ~24%.

FINANCIAL DISCLOSURE

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REFERENCES CITED

Abdallah, A. F., Jawaid, M., Mohamed, A. Z., Tahir, P. M., Osman F. A., and Abdullah, U. H. (2023). "A review on alkaline sulphite anthraquinone methanol as an alternative pulping process for non-wood biomass," *Biomass Conversion and Biorefinery* 2023, available online. DOI: 10.1007/s13399-023-05006-x

Dahlbom, J., Olm, L., and Teder, A (1990). "The characteristic of MSS-AQ pulping – A new pulping process," *TAPPI J*. 73, 257-261.

Dutt, D., Upadhyaya, J. S., and Tyagi, C. H. (2010). "Studies on *Hibiscus cannabinus, Hibiscus sabdariffa,* and *Cannabinus sativa* pulp to be a substitute for softwood pulp - Part 1: AS-AQ delignification process," *BioResources* 5(4), 2123-2136.

Dutta, T., and Biermann, C. J. (1989). "Kraft pulping of Douglas-fir with 1,4-dihydro-9,10-dihydroxy anthracene," *TAPPI J*. 67(6), 175-177.

Erişir, E, Gümüşkaya, E, Kirci, H, Misir, N. (2015). "Alkaline sulphite pulping of Caucasian spruce (*Picea orientalis* L.) chips with additions of NaBH4 and ethanol," *Drewno* 58(194), 89-102. DOI: 10.12841/wood.1644-3985.067.07

Furuya, J. (1984). "9% production gain with quinone-additive kraft pulping in a batch digester," *TAPPI J*. 67(6), 82-85.

Hanhikoski, S., Warstwa, E., Varhimo, A., Niemela, K., and Vourinen, T. (2016). "Sodium suphite pulping of Scots pine under neutral and mildly alkaline conditions (NS pulping)," *Holzforshung* 70(7), 603-609. DOI:10.1515/hf-2015-0099.

Hedjazi, S., Kordsachia, O., Patt, R., Jahan Latibari, A., and Tschirner, U. (2008b). "Alkaline sulfite-anthraquinone (AS/AQ) pulping of wheat straw and totally chlorine free (TCF) bleaching of pulps," *Industrial Crops Products* 29, 27-29. DOI: 10.1016/j.indcrop.2008.03.013

Hedjazi, S., Kordsachia, O., Jahan Latibari, A., and Tschirner, U. (2009). "Alkaline sulfite/anthraquinone (AS/AQ) pulping of rice straw and TCF bleaching of pulps," *APPITA J*. 62(3),137-145

Henriksson, G., Germgård, U., and Lindström, M. E. (2024). "A review on chemical mechanisms of kraft pulping," *Nordic Pulp & Paper Research Journal* 2024, published online. DOI: 10.1515/npprj-2023-0015.

Imada, S. E., Fairchild, R. S., and Tay, C. H. (1987). "Effects of liquor pH on sulphite. quibnone cooking of black spruce for chemimechanical pulp," *Journal of Pulp and Paper Science* 13(2), J39-J44.

Ingruber, O. V., and Allard, G. A. (1973). "Alkaline sulfite pulping for "Kraft" strength," *Pulp and Paper Magazine of Canada* 74(11), 84-99.

ISO 2470 (1999). "Paper, board and pulps – measurement of diffuse blue reflectance factor. ISO brightness," International Organization for Standardization, Geneva, Switzerland.

Kettunen, J., Virkola, N. E., and Yrjala, I. (1979). "The effect of anthraquinone on neutral sulphite and alkaline sulphite cooking of pine," *Paperi ja Puu [Paper and Timber]* 61(11), 685-700

Kordsachia, O., Jukka, F., Csóka, L., and Winkler, A. (2008). "ASA and kraft pulping of poplar," *Cellulose Chemistry and Technology* 42(1-3), 23-29.

Kubes, G. J., Wang, B., and Keskin-Schneider, A. (1995). "Catalyzed sulphite and semi-chemical pulping," *Research on Chemical Intermediates* 21(3-5), 489-501.

Jahan Latibari, A., Hossein, M. A., and Hosseinpour, R. (2011). "Application of alkaline sulfite pulping on corn stalks," *BioResources* 6(1), 48-58.

McCubbin, N. (1997). "Yield improvements possible with O_2 delig., digester modifications," *Pulp & Paper* 71(6), 93-97.

McDonough, T. J., Van Drunen, V. J, and Paulsoc, T. W. (1985). "Sulphite-anthraquinone pulping if southern pine for bleachable grades," *Journal of Pulp and Paper Science* 11(6), J167-J175.

MacLoed, J. M., and Fleming, B. I. (1983). "Delignification rates of alkaline AQ processes," *TAPPI J*. 66(12), 81-82.

MacLoed, J. M. (1987). "Alkaline sulphite-anthraquinone pulps from softwood," *Journal of Pulp and Paper Science* 13(2), J44-J49.

MacLoed, M. (2007). "Top ten factors in kraft pulp yield," *Paperi ja Puu [Paper and Timber]* 89(4), 1-7.

Mróz, W., and Surewicz, W. (1981). "Wpływ poziomu delignifikacji drewna na charakterystykę mas celulozowych [The influence of the level of wood delignification on the characteristics of cellulose pulps]," *Przegląd Papierniczy* 37(1), 3-7.

Moradbak, A., Tahir, P. M., Mohamed, A. Z., Peng, L. C., and Halis, R. (2016). "Effects of alkaline sulfite anthraquinone and methanol pulping conditions on the mechanical and optical paper properties of bamboo **(***Gigantochloa scortechinii*)," *BioResources* 11(3), 5994-6005. DOI: 10.15376/biores.11.3.5994-6005

Paananen, M., Rovio, S., Liitiä, T., and Sixta, H. (2015). "Effect of hydroxide ion concentration in alkaline sulphite anthraquinone (ASA) pulping – A comparative study," *Holzforshung* 69(6), 661-666. DOI: 10.1515/hf-2014-0303

Palenius, I. (1979). "Kraft pulp – Are there viable alternatives?," *Pulp Paper International* 21(3), 64-67.

Patt, R., and Kordsachia, O. (1986). "Production of pulps using alkaline sulphite solutions with the addition of anthraquinone and methanol," *Das Papier* 40(10a), V1-V8.

Parsad, B., Gratzl, J., Kirkman, A., Jameel, H., Rost, T. and Magnotta, V. (1994). "High-kappa pulping and extended oxygen delignification decreases recovery cycle load," *TAPPI J.* 77(11), 135-147.

PN-85/P50095.02 (1985). "Fibrous papermaking semi-finished products. Determination of degree of pulping of fibrous cellulose pulp. Determination of kappa number," Polish Committee for Standardization, Warsaw, Poland.

Sahab, H., Kordsachia, O., Patt, R., Jahan Latibari, A., and Tschirner, U. (2008). "Bagasse alkaline sulfite-anthraquinone (AS/AQ) pulping and totally chlorine free (TCF) bleaching," *Holzforschung* 62(2), 142-148. DOI.org/10.1515/HF.2008.044.

Silva Junior, F. G., and Barrichello, L. E. G. (1995). "Conversion of the kraft process in soda-DDA (disodium salt of 1,4-dihydro-9,10-dihydroxy anthracene) for eucalypt," in: *Proceedings of the 1995 Pulping Conference*, Vol. 2, 757, Chicago, IL, USA.

Stradal, M. (1985). "Vapour phase pulping for lineboard by the alkaline sulphite-anthraquinone process," *Journal of Pulp and Paper Science* 11(5), J155-J160.

Usta, M., Ergolu, H., and Karaoglu, C. (1999). "ASAE pulping of wheat straw (*Tritacum aestivum* L.)," *Cellulose Chemistry and Technology* 33(1-2), 91-102.

Virkola, N.-E., Pusa, R., and Kettunen J. (1981). "Neutral sulphite AQ pulping as an alternative to kraft pulping," *TAPPI J.* 64(5), 103-107.

Vogel, A. I. (1984). *Preparatyka Organiczna [Organic Preparation]*, PWN Press, Warszawa, Polska.

Wandelt, P. (1979). "The effect of anthraquinone on neutral sulphite and alkaline sulphite cooking of pine," *Paperi jaa Puu [Paper and Timber]* 61(11), 685-700.

Wandelt, P. 1992. "Wpływ metanolu na roztwarzanie sosny metodą obojętnosiarczynowo-antrachinonową [The effect of methanol on pine pulping by the neutral sulfite-anthraquinone method]," *Przegląd Papierniczy* 48(11), 364-366.

Wandelt, P., and Surewicz, W. (1983). "Catalyzed alkaline sulfur-free pulping. Selection of the catalyst and its dose," *Cellulose Chemistry and Technology* 17(3), 543-552.

Wandelt, P. (1990). "Praktyczne aspekty stosowania antrachinonu w zakładach celulozowo-papierniczych [Practical aspects of the use of anthraquinone in pulp and paper mills]," *Przegląd Papierniczy* 46(8-9), 281-285.

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