Quality Types of Pine (*Pinus sylvestris*) Kraft Pulps and the Boundary Values of Their Kappa Numbers, Yield, and Reject Content in Digester Pulp

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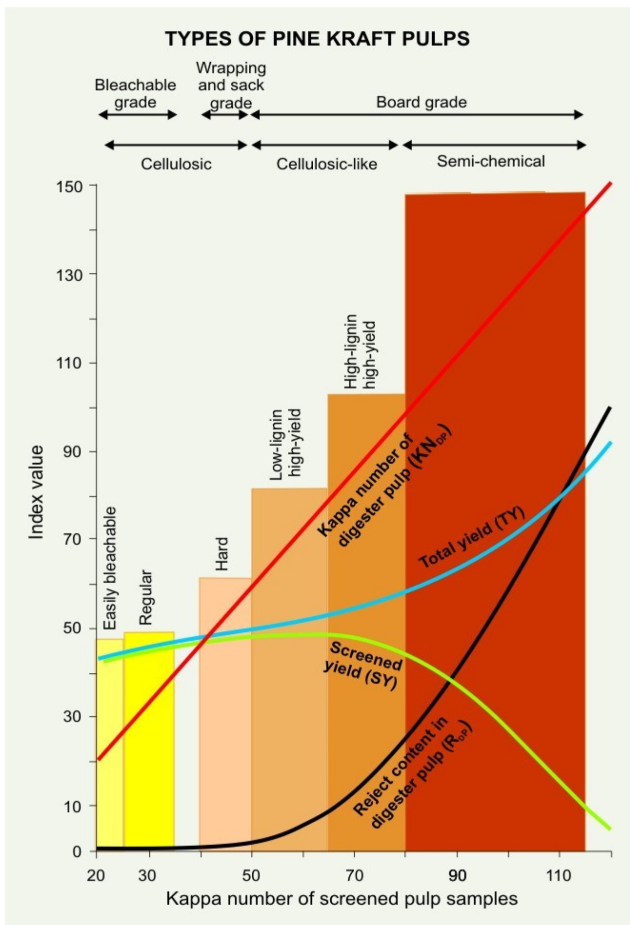
GRAPHICAL ABSTRACT



Quality Types of Pine (*Pinus sylvestris*) Kraft Pulps and the Boundary Values of Their Kappa Numbers, Yield, and Reject Content in Digester Pulp

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Dependence curves for the kappa number of digester pulp (KN_{DP}), total pulp yield (TY), screened pulp yield (SY), and reject content in digester pulp (R_{DP}) as a function of the kappa number of screened pulp (KN_{SP}) were determined based on the results of several dozen kraft pulping tests of pine wood chips (*Pinus sylvestris*). These curves were then analyzed to assess whether their course could be used to distinguish qualitative types of pine kraft pulps and to determine the boundary values of the KN_{DP}, TY, SY, and R_{DP} indices for these types. Relationships of the form R_{DP} = $f(KN_{SP})$ were found to be particularly useful for this purpose. The identified types of pine kraft pulps and the limiting values of the parameters used to assess pulping process efficiency are presented in a table at the end of the paper.

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Keywords: Unbleached pine kraft pulps; Quality types; Kappa numbers; Yields; Reject contents; Boundary values of these indices

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INTRODUCTION

Pulping wood chips using the kraft method is currently the most widely used process for producing pulps for paper and board manufacturing. Pulps used in papermaking include both pulps intended for unbleached applications and bleached pulps. Such pulps can be produced from both softwood and hardwood species.

In the case of softwood kraft pulps intended for bleaching (bleached grade), two main groups can be distinguished. The first group comprises conventionally produced pulps obtained in traditional pulp mills, commonly referred to as *regular pulps*. The second group includes *easily-bleachable pulps* produced in mills using modified pulping techniques, which enable bleaching with reduced amounts of bleaching chemicals. The criteria for distinguishing these groups appear to be relatively well established. The first group is defined by a screened pulp kappa number (KN_{SP}) in the range of 25 to 35, whereas for the second group the KN_{SP} after pulping is lower than 25.

In contrast, the criteria used to classify softwood kraft pulps intended for unbleached applications are much less clearly defined. Pulps used in the production of wrapping and sack paper, and board applications undoubtedly belong to this group. The distinction between these pulp types is supported by data reported in articles by Kleppe (1970), who referred to them as paper grade pulps and board grade pulps and assigned them kappa number ranges of 35 to 60 and 60 to 120, respectively. However, Kleppe and other authors, such as McGovern (1972) and Smook (1994), do not provide a clear justification for the selection of these kappa number ranges for the pulp groups discussed.

Although the existence of a group of pulps intended for the production of wrapping and sack papers from softwood does not raise major doubts, the separation of only board grade pulps as a group clearly distinguishable from sack grade pulps may be questioned. Surewicz (1956, 1957) and Szwarcsztajn (1957) divided this group into *hard pulps*, *high-yield kraft pulps*, and *semi-chemical kraft pulps*. However, they did not specify the corresponding kappa numbers, providing only the ranges of wood yield, defined as 50 to 60% for the former and 60 to 80% for the latter. Moreover, Wandelt (1996) in his book *Technology of Fibrous Pulps* divides unbleached kraft pulps into *easily-bleachable* (KN=15-35), *sack hard* (KN=35-70), and *high-yield kraft*, classifying the latter type to the group of semi-chemical kraft pulps without specifying the KN.

Consequently, people working in pulp mills who are not papermaking graduates or even students of this field who learn from the few textbooks available may experience some frustration due to the uncertainty regarding the types of kraft pulps that can be produced from softwood and the lack of clearly documented scientific data supporting the classification of these pulp types.

With this in mind, a series of experiments was carried out involving the kraft pulping of pine (*Pinus sylvestris*) wood chips. Dependence curves for the main process evaluation parameters—namely the kappa number of digester pulp (KN_{DP}), total pulp yield (TY), screened pulp yield (SY), and reject content in digester pulp (R_{DP})—were determined as functions of the kappa number of screened pulp (KN_{SP}). The objective was to obtain experimental evidence that would allow the identification of different types of unbleached kraft pulps and the determination of the boundary values of the above-mentioned indices for each pulp type.

EXPERIMENTAL

Fibrous Raw Materials and Chemicals Used for this Research

Pine wood chips (*Pinus sylvestris*) were obtained from a Polish pulp mill. The chips were used in the air-dry state. Prior to pulping, they were classified by screening using a Santasalo-Sohlberg chip classifier. Only wood particles that passed through a sieve with 22 mm diameter holes and were retained on a sieve with 13 mm diameter holes were used in the experiments. Additionally, chips thicker than 4 mm were separated from those sorted in this manner and used for testing only after that step.

Sodium hydroxide (NaOH) and sodium sulphide (Na_2S) were purchased from POCH (Poland), with a pure component content of 99% and 98%, respectively.

Pulping of Pine Wood Chips

Determining the dependence of the TY, SY, and R_{DP} on KN_{SP}

All experiments were carried out in 200 mL autoclaves placed in a rotating six-section Santasalo-Sohlberg AB laboratory digester heated with hot air. In each experiment, 50 g of oven-dry (o.d.) wood chips were used.

The cooking liquor containing the required amount of alkali was prepared through NaOH and Na_2S dissolution in distilled water. This water was used also as the make-up liquid. The active alkali charge ranged from 13 to 25% as NaOH based on oven-dry wood. The sulfidity of the cooking liquor was 25%. The liquor-to-wood ratio was 3.7.

The initial temperature was 20 °C. The heating time to the maximum temperature was 90 min, and the cooking time at this temperature ranged from 60 to 150 min.

After the designated pulping time, the autoclaves were cooled in water for approximately 20 min. The digested chips were quantitatively transferred to a porcelain funnel lined with dense cheesecloth to separate the black liquor and to pre-wash the chips with water. After the initial washing step, the pulped chips were transferred to a container, filled with water, and left overnight to allow further washing of the pulped chips by diffusion. The chips were then drained and disintegrated for 3 min in a laboratory propeller disintegrator, which resulted in defibering of the chips and the formation of digester pulp (DP). The pulp was subsequently dried at room temperature, and its dry matter content was determined in order to calculate the total (digester) pulp yield (TY) according to Eq. 1,

$$TY = (m_{DP} / m_W) \cdot 100 \ [\%] \qquad (1)$$

where m_{DP} is the mass of absolutely dry digester pulp and m_W is the oven-dry mass of the wood used in the experiment.

The dried pulp samples were then soaked in water overnight, disintegrated in a laboratory disintegrator, and screened in a Weverk laboratory screen equipped with slots 0.2 mm wide. This procedure enabled the determination of the mass of unpulped wood particles in the sample, *i.e.*, reject (m_R).

Based on this value, the reject content in digester pulp (R_{DP}) and the screened pulp yield (SY) were calculated using Eqs. 2 and 3:

$$R_{DP} = (m_R / m_{DP}) \cdot 100 \ [\%] \qquad (2)$$

$$SY = [(TY - TY \cdot R_{DP}] \cdot 100 \ [\%] \qquad (3)$$

Determining the mathematical dependence of the KN_{DP} from KN_{SP}

The experiments were performed using the same procedure as described above. The only variable parameter was the charge of active alkali added to the wood.

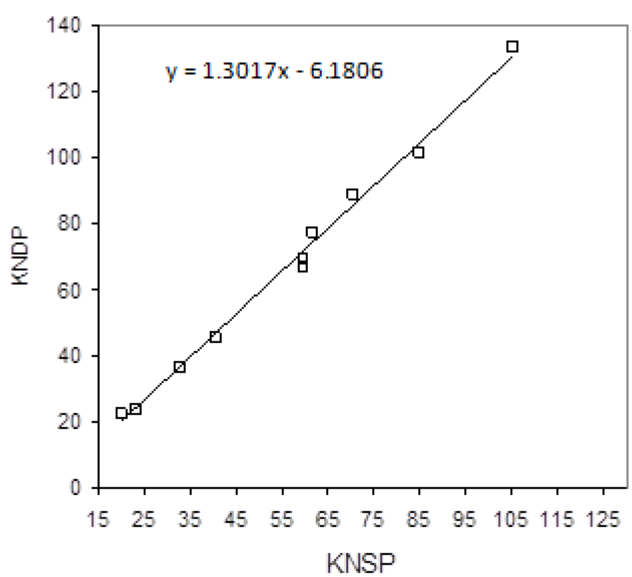

Fig. 1. Dependence of the kappa number of screened pulp (KN_{SP}) and kappa number of digester pulp (KN_{DP})

These experiments differed from the previous series in that the rejects were separated from the screened pulp and subsequently disintegrated twice in a Bauer company laboratory disc refiner with a disc gap of 0.1 mm. After determination of the kappa number of the screened pulp (KN_{SP}), the treated rejects were added back to the screened pulp samples. This procedure resulted in well-defibered digester pulps, which allowed reliable determination of the kappa number of digester pulp (KN_{DP}). The results of the KN_{SP} and KN_{DP} determinations obtained in these experiments are presented in Fig. 1. The relationship between these parameters enabled the derivation of an equation relating KN_{SP} to KN_{DP} for pine wood chips pulped using kraft pulping method. This equation was subsequently used to calculate the KN_{DP} values for the pulps obtained in the first part of the study.

Kappa number (KN)

The kappa number of pulp samples were determined in accordance with the PN-70/P-50095 standard *i.e*., using 0.1 n $KMnO_4$ as lignin oxidizer.

Visualization of pulps

The MorFi apparatus (Techpap, France) was used to demonstrate the different contents of shives in pine kraft pulps of KN_{DP} 30 and 85.

RESULTS AND DISCUSSION

As mentioned in the Introduction, a certain problem for some young technologists is to determine on what basis the boundary values of kappa number of softwood kraft pulps (mainly pine) intended for the production of pulps used in the manufacture of white, wrapping and sack, paperboards or even more raw paper products have been established. To determine this basis, Fig. 2 presents the dependence of KN_{DP}, TY, SY, and R_{DP} on KN_{SP}. These relationships are indicated in the figure by red, blue, green, and black curves, respectively. Below, the course of each of these colored curves is discussed with regard to their potential use in determining the boundary values of kappa number corresponding to a number types of softwood kraft pulps produced in the global pulp industry.

The Red Curve

This curve represents the calculated relationship between KN_{DP} and KN_{SP}. The KN_{DP} values for all pulp samples were calculated using the equation: $KN_{DP} = 1.3017 \cdot KN_{SP} - 6.1806$, the derivation of which is described in the methodology section. Because this equation represents a linear function, the relationship between KN_{DP} and KNSP shown in Fig. 2 is also linear. However, this type of relationship (linear) does not allow the determination of any boundary values of KN_{SP}, KN_{DP}, TY, SY, and R_{DP} for different types of kraft pulps produced in many kraft pulp mills in the world.

The Blue Curve

This curve represents the trend line describing the relationship between the total pulp yield (TY) and the kappa number of screened pulp (KN_{SP}) for the analyzed pine kraft pulp samples. As can be seen, the curve initially increases approximately linearly and then, starting from $KN_{SP} \approx 60$, it follows a curved trajectory. A similar relationship was reported by Bristow *et al*. (1968). The curve indicates that the TY at $KN_{SP} = 20$ is approximately

42.5%, whereas at KN_{SP} = 80 it reaches about 58%. However, as in the case of the previously discussed curve, the relatively uniform increase of TY with increasing KN_{SP} does not allow the determination of clear boundary values of KN_{SP}, KN_{DP}, TY, SY, and R_{DP} for different types of pine kraft pulps intended for the production of white, wrapping, and sack, and board papers.

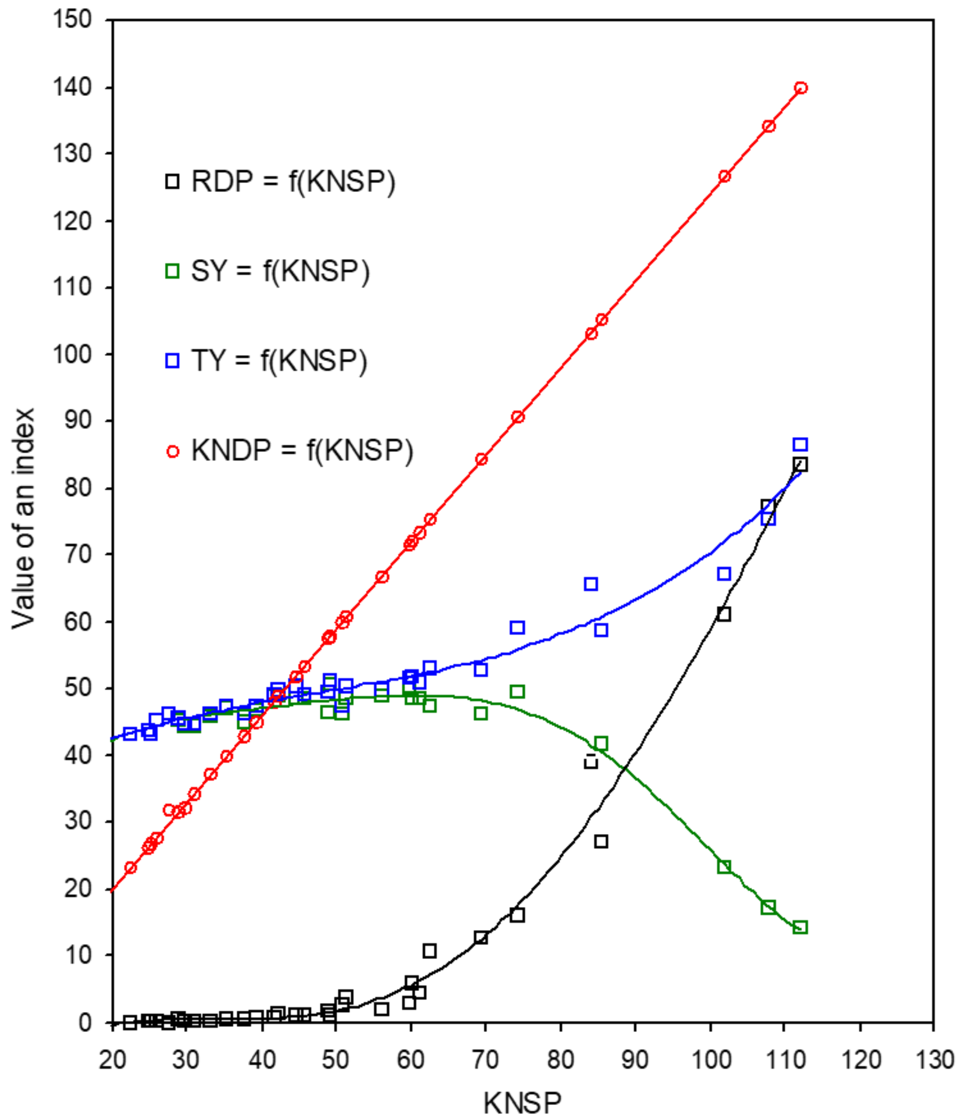

Fig. 2. Kappa number of digester pulp (KN_{DP}), total yield (TY), screened pulp yield (SY) and content of reject in digester pulp (R_{DP}) as a function of kappa number of screened pulp (KN_{SP})

The Green Curve

This curve represents the trend line describing the relationship between the screened pulp yield (SY) and the kappa number of screened pulp (KN_{SP}). In comparison with the red and blue curves, this relationship is more informative for determining the limiting values of kraft pulping process indices for different types of pulps produced from pinewood in industrial practice. Initially, the curve gently rises almost linearly. It then transforms into a segment of a circular arc where it reaches its maximum value, after which it drops quite sharply almost linearly up to $KN_{SP} \approx 110$.

This behavior theoretically allows the pulp mills the KN_{SP} of pulp intended for the production of wrapping and sack grade papers to increase to approximately 60 units. However, when taking into account the corresponding reject content ($R_{DP} \approx 7\%$), as well as the advantage of producing such papers from pulps with a low content of shives and with fibers that have not been excessively shortened during defibering in a disc refiner, the most appropriate KN_{SP} range for pine kraft pulps intended for the production of high-quality wrapping and sack papers can be considered to be 40 to 50 units. This range corresponds approximately to KN_{DP} values of 46 to 59 units, TY of 48 to 50%, SY of 47 to 48.2%, and R_{DP} of 1 to 2%.

Further analysis of the green curve indicates that it unfortunately does not allow the determination of boundary values for board pulp grades with higher KN_{SP} and KN_{DP} values above approximately 50 and 60, respectively. This is due to its relatively gentle slope and the absence of clearly defined inflection points.

A relatively high SY in the KN_{SP} range of 40 to 50, combined with a still low R_{DP} value, could also suggest the potential use of this type of pulp for bleaching. However, the corresponding residual lignin content of 6 to 8% is clearly too high when considering the demand for chlorine dioxide and the discharge of wastewater containing increased amounts of depolymerized lignin and chlorine compounds to wastewater treatment plants. Therefore, as mentioned earlier, the kraft pulping of pine wood intended for bleachable pulps is carried out to lower kappa numbers. Conventionally, the kappa number of screened pulp usually falls within the range of 25 to 35 units (most often 25–30), which corresponds to a residual lignin content of approximately 3.8 to 5.4% in the pulp. Pulps produced within this kappa number range are commonly referred to as bleached grade kraft pulps. Unfortunately, as shown in Fig. 2, reducing the kappa number of pulps intended for bleaching to this range results in a decrease in both TY and SY to approximately 44.2 to 46.9% and 44.1 to 46.4%, respectively. These values are typical for pine kraft pulps (MacLeod 2007).

It is well known that modern pulping technologies and process modifications, such as SuperBatch and Lo-Solids cooking enable the production of kraft pulps with $KN_{SP} < 25$ while maintaining higher pulp yields than those indicated by the green curve in Fig. 2. In addition, these processes lead to a smaller reduction in the intrinsic viscosity of the pulp in CED solution (Mohr *et al*. 1994; Westin *et al*. 2002). Due to their lower residual lignin content and the resulting improvement in bleachability such pulps can be classified as *easily-bleachable kraft pulps*.

The Black Line

This curve represents the trend line describing the relationship between R_{DP} and KN_{SP}. In the KN_{SP} range of approximately 20 to 50, the curve is almost linear and characterized by a relatively low slope. After exceeding $KN_{SP} \approx 50$, the course of the curve changes. It begins to increase along a curved trajectory up to approximately $KN_{SP} = 80$, with a progressively increasing slope. Beyond this point, the relationship becomes nearly linear again, but with a relatively steep and almost constant slope.

This curve enables the estimation of the R_{DP} value in digester pulp for a given KN_{SP}. Analyzing its course with respect to the determination of boundary values of KN_{SP}, TY, SY, and R_{DP} for regular-grade pulps**,** it can be concluded that the KN_{SP} range of 20 to 35 for pine kraft pulps is appropriate due to the low reject content observed in digester pulp within this range. The amount of rejects in the pulp samples is sufficiently small in that their separate repulping and return to the screened pulp is not economically justified.

Instead, they can be repulped together with another batch of wood chips, where their small quantity does not significantly affect the pulping process or the properties of the resulting pulp.

As discussed earlier, for wrapping and sack-grade pulps selecting a KN_{SP} range of 40 to 50 (corresponding to KN_{DP} values of approximately 46 to 59) appears appropriate. The relatively low R_{DP} and KN_{SP} levels are advantageous as they minimize the negative impact of fiber bundles and shives on pulp properties. Moreover, as noted by Giertz (1963), this KN_{SP} range corresponds to a TY range of 48 to 50%, which remains below the critical interval of 50 to 60%, where the properties of pine kraft pulp change significantly. These changes include, for example, a substantial increase in beating time, a decrease in the bonding activity of the fibre surface (due to the deposition of hydrophobic lignin in kraft pulps), and a marked reduction in the number of fibres per gram of pulp.

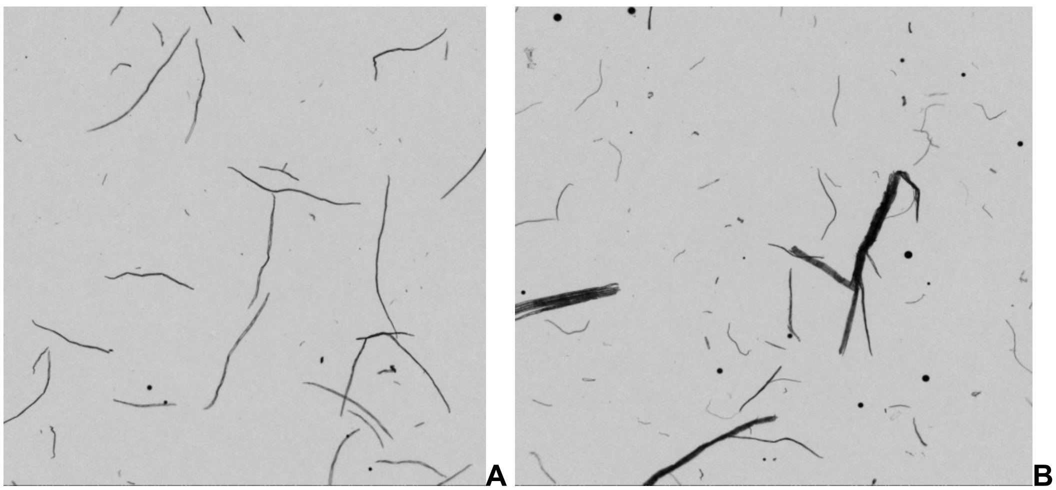

Fig. 3. Photo of KN_{DP} 30 and KN_{DP} 85 (KN_{SP} ≈ 70) industrial pulps from MorFi apparatus showing well-defibred industrial bleached grade pulp and industrial board grade pulp not fully defibered with well visible shives contained in this pulp

In addition, the low reject content allows the use of mild mechanical defibering of the digester pulp, thereby avoiding the need for more intensive refining in a disc refiner, which can lead to fiber damage. This is particularly important for high quality pulps intended for the production of wrapping and sack papers called by some *hard pulps* (Surewicz 1956; Wandelt 1996).

As mentioned, after exceeding $KN_{SP} \approx 50$, the $R_{DP} = f(KN_{SP})$ curve begins to increase along a curved trajectory up to approximately $KN_{SP} = 80$, with a progressively increasing slope, and then nearly linear, with a relatively constant slope. Considering the behavior of the $SY = f(KN_{SP})$ and $TY = f(KN_{SP})$ curves, this pattern according to author of this article allows for the distinction of three types of board grade pine kraft pulps in the $KN_{SP} > 50$ range:

- *Low-lignin high-yield pulps*: KN_{SP} 50 to 65 and KN_{DP} 59 to 78, with SY remaining high at 48.2 to 49%, TY of 50 to 53%, and R_{DP} of 2 to 9%. These pulps require standard mechanical defibering after pulping.
- *High-lignin high-yield pulps*: KN_{SP} 65 to 80 and KN_{DP} 78 to 98, where SY decreases from 49% to 44.5%, TY increases to 53 to 58%, and R_{DP} rises to 9 to 25%. These pulps require intensified mechanical defibering after pulping.

- *Semi-chemical kraft pulps*: KN_{SP} 80 to 115 and KN_{DP} 98 to 143, with SY decreasing from 44.5% to 12%, TY of 58 to 86%, and R_{DP} as high as 25 to 90%. These pulps require the most intensive mechanical defibering after pulping.

The data presented in Fig. 2, together with the analyses described above, allow the compilation of boundary values for KN_{SP}, KN_{DP}, TY, SY, and R_{DP} for different types of unbleached pine kraft pulps. These pulps are used for the production of writing and printing papers, wrapping and sack papers, and board papers. The resulting values are summarized in Table 1.

Table 1. Boundary Values of KN_{SP}, KN_{DP}, TY, SY, and R_{DP} for Different Types of Unbleached Pine Kraft Pulps Used in the Production of Writing and Printing Papers, Wrapping and Sack Papers, and Boards

Name of Pulps / Index	Bleached grade		Wrapping and sack grade	Board grade		
	Easily-bleach-able	*Regular*	*Hard*	*Low-lignin high-yield*	*High-lignin high-yield*	*Semi-chemical*
KN_{SP}	<25 np. 20	25 to 35	40 to 50	50 to 65	65 to 80	80 to 115
KN_{DP}	20	27 to 40	46 to 59	59 to 78	78 to 98	98 to 143
TY, % o.d. wood	42.5	44.2 to 46.9	48 to 50	50 to 53	53 to 58	58 to 86
SY, % .d. wood	42.4	44.1 to 46.4	47 to 48.2	48.2 to 49	49 to 44.5	44.5 to 12
R_{DP}, %	<0.2	0.2 to 0.6	1 to 2	2 to 9	9 to 25	25 to 90
The nature of mechanical defibering	Not needed	Not needed	Mild	Normal	Intensified	Intense

CONCLUSIONS

1. The kappa number range of 20 to 35 for *easily-bleachable* and *regular* pulps groups is well selected due to the low reject content in digester pulp for these pulps within this range. This low R_{DP} allows for recovery of the rejects through repulping without the need for its mechanical refining.

2. The KN_{SP} range of 40 to 50 (KN_{DP} 46 to 59) for high-quality wrapping and sack grade pine kraft pulps (*i.e.*, *hard pulps*) is also appropriate. Within this range, the relatively low R_{DP} (1 to 2%) in digester pulp enables the use of mild mechanical defibering of the pulped chips, resulting in low fibre bundles and shives content digester pulps, minimal fiber damage, and highest strength properties of fibres and pulps.

3. The curves for R_{DP} and SY *vs.* KN_{SP} indicate the possibility of distinguishing three types of board grade pine kraft pulps within the ranges KN_{SP} = 50 to 115 and KN_{DP} = 59 to 143:

- *Low-lignin high-yield pulps* (1), R_{DP} 2 to 9%.
- *High-lignin high-yield pulps* (2), R_{DP} 9 to 25%.
- *Semi-chemical kraft pulps* (3), R_{DP} 25 to 90%.

4. The need to separate these three pulp groups is suggested by the changes in the manner in which R_{DP} and SY changes. Specifically, there is a transition from linear growth of R_{DP} to an arc-shaped course in the range of maximum values of SY (group 1); arc-shaped growth of R_{DP} in the range of arc-shaped decreasing of SY (group 2); and nearly linear growth of R_{DP} in the range of almost linear sharp decrease of SY (group 3).

5. It seems that low-lignin board grade pulps could also be used in some pulp and paper mills as sack grade pulps. In such cases, this group of pulps could be referred to as *high-lignin* sack grade / *low-lignin* board grade.

6. For practical purposes, some of the boundary values of KN_{SP}, KN_{DP}, TY, SY, and R_{DP} presented in Table 1 can be rounded. For example, the KN_{DP} range of 98 to 143 for semi-chemical kraft pulps can be rounded to 100 to 140.

FINANCIAL DISCLOSURE

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