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THE INFLUENCE OF PROCESS VARIABLES ON THE STRENGTH PROPERTIES OF NSSC BIRCH PULP. TOWARDS THE LIMITS OF OPTIMIZATION: PART ONE – THE EFFECT OF LIQUOR RATIO

The aim of this work was to establish the best mechanical and strength properties of NSSC pulp using operating conditions at which the lowest (optimal) spent liquors, cooking temperature and time of treatment can be obtained. Minimal and maximum limits of independent variables were proposed using real mill conditions as starting points. The analyzed variables were: cooking time (13 to 15.5 min), cooking temperature (172 to 179°C), liquor- to- wood ratio (from 1.2 to 2.2). In spite of the extremely narrow ranges of controlled cooking variables, a large database and combined statistical methods (analysis of variance, parallel coordinates, principal component analysis) allowed the distinction of the optimal range limits of studied technological factors determining the tested pulp's properties. The mechanical and strength testing of the pulp's sheets showed that the analyzed time, temperature and liquor- to- wood ratio influenced the CMT, SCT, Tear strength and to some extent Burst strength.

Keywords: NSSC, pulp, liquor ratio, statistical methods

Introduction

Neutral sulfite semi chemical (NSSC) pulp accounts for approximately 5-7% of the overall production of paper pulp. The main advantage of this type of pulp are that it provides fibers of a very high quality for special types of paper, especially the so-called microwave for multilayer cartons (corrugated medium). NSSC pulp may be used as such or it may also partially replace other pulp from wood,

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lignocellulosic residues or old paper during the manufacture of various products such as printing and writing paper, tissue paper, cardboard, bag grades and other products [Farrington, Hickey 1989; Odom 1991; Myers et al. 1996; Area et al. 1997; Ahmadi et al. 2010].

Although the relatively traditional process of neutral sulfite pulping maintains its industrial importance, the question of the recovery of spent liquor chemicals still needs to be resolved. Most producers use the cross recovery system with Kraft spent liquors, while others have fluidized bed combustion systems. In every case, the problem is the relatively high inorganic to organic ratio in spent liquors and that is why the liquor- to- wood ratio is (among others) such an important technological factor [Area et al. 2001a, 2001b].

The pulping process of various wood and non-wood plants has been analyzed with the use of many mathematical models and statistical methods allowing the estimation of pulp quality in terms of process variables and determining optimal operating conditions. Most of these models were based on delignification kinetics and only a few took into consideration the influence of process variables on pulp quality [Jimenez et al. 1999, 2000, 2004]. Moreover, most of these models were established by applying the results of laboratory scale experiments only and with arbitrary admitted ranges of variables.

The aim of this work was to examine the influence of extremely low changes in industrial operating variables (liquid/solid relation, temperature, pulping time) on the mechanical and strength properties of the NSSC pulp paper sheets (CMT, SCT, Burst and Tear strength) obtained, using mathematical and statistical methods.

Materials and methods

Industrial chips obtained from birch trees growing in Poland (*Betula verrucosa*) were used as the raw material. The chips included the following fractions: >O45 – 1.1%, >II8 – 5.7%, >O7 – 91.0%, >O3 – 2.1%, the rest – 0.1% (O and II mark holes and slots, diameter in mm according to Brecht-Holl classification) [SCAN–CM–40:01]. The birch wood contained 82.4% holocellulose, 27.31% α -cellulose, 31.44% lignin by dry matter weight.

All cooking experiments were carried out on a real industrial NSSC production line with a controlled capacity and with an 82% average process yield. Pulping: continuous cooking, a vapour-gas phase technique, pulp kappa no 120 \pm 10. The most important units composing the pulp line were: an atmospheric chip bin, a plug screw feeder, a pressurized impregnator, a continual digester and a cooked chip disintegration refiner. After the release of air at the chip bin, the wood was squeezed by the screw feeder and then pushed to the pressurized impregnator. The impregnator was connected directly with the digester and that construction had the

same operational pressure 9.2 bar. The initial cooking liquor concentration was the same during all the experiments ($165\text{g/dm}^3 \text{Na}_2\text{SO}_3$; $50\text{g/dm}^3 \text{Na}_2\text{CO}_3$). After processing at different conditions of liquor-to-wood ratio, at a fixed temperature of $178/179^\circ\text{C}$ and cooking time of 14.5 min, the chips were defibred by a double-disc disintegration refiner with a concentration of 36% (Andritz Sprout Bauer, 2.5 MW, optimal energy consumption 130 kWh/Mg). The retention time of the line was calculated for approx. 1 hour.

For each studied technological parameter (liquor-to-wood ratio, time and temperature of cooking), the obtained pulp samples were refined in a PFI laboratory mill to reach four Schopper-Riegler degrees: 20 °SR, 25 °SR, 30 °SR, 35 °SR. After Schopper-Riegler freeness tests from all pulp samples, hand sheets were made. From the dried and conditioned paper sample, four strength properties were examined: SCT – short crush test [EN/ISO 9895], CMT – Concora medium test [EN/ISO 7263], Tear strength [EN 21974] and Burst strength [EN/ISO 2758].

Liquor-to-wood ratio

Pulp samples were collected after cooking with 1.4, 1.5, 1.7, 1.8 and 2.2 liquid-to-wood ratios (l/w). The other technological variables (temperature and cooking time) were determined with l/w ratio 1.8 and 1.55. The total number of observations used for l/w ratio analysis: CMT (373), SCT (642), Burst strength (442), Tear strength (150). The number of observations resulted from the different number of paper sheets qualified as convenient for strength analysis. In particular, the compression strength of paper (CMT, SCT) is measured at high grammage 130 g/m^2 and all the paper sheets which did not have an appropriate weight per unit area and caused the risk of bad readings were not analyzed.

Statistical analysis

Firstly, the normality of the distribution of the CMT, SCT, Tear and Burst strength was tested using Shapiro-Wilk's normality test [Shapiro, Wilk 1965]. A two-way analysis of variance (ANOVA) was carried out to determine the effects of liquid-to-wood ratio, Schopper-Riegler numbers and interaction of liquid-to-wood ratio \times Schopper-Riegler numbers on the variability of CMT, SCT, Tear and Burst strength development. The least significant differences (LSDs) for each variable were calculated and, on this basis, homogeneous groups for the analyzed variables were determined. The relationship between CMT, SCT, Tear and Burst strength were estimated on the basis of correlation coefficients. The relationship between the analyzed properties was presented in the form of scatter-plot [Kozak et al. 2010]. The application of principal components analysis (PCA) made it possible to find on the plane the graphic dispersion of pairs of liquid-to-wood ratio

and Schopper-Riegler degrees characterized with regard to all properties treated together.

The parallel coordinate plot is proposed as an efficient tool for liquid-to-wood ratio \times Schopper-Riegler freeness interaction visualization [Kozak 2010]. Analysis of the data was performed using the statistical package GenStat v. 10.1 [GenStat 2007].

Results and discussion

Because of the variety of effects of chemical and mechanical treatment on final product properties, it becomes especially important for the papermaking process to understand how the different technological factors affect the technological practice of NSSC pulping.

Little differences among the controlled operating conditions on the industrial-scale production line (liquor-to-wood ratios, temperature, cooking time) make the choice of both appropriate statistical tools and the possession of a sufficient database very important. As the most appropriate indices for the evaluation of the technological efficiency, first of all CMT [N] and SCT [kN/m] were admitted, then Burst [kPa] and Tear [mN]. Literature in this area is very limited but it is generally accepted that the most important property of fluting papers is the compression strength: CMT and SCT. CMT is a measure of opposition to the crushing of the flute after it is developed by the corrugator. The use of the SCT strength index has been found to be an accurate indicator of refining effect and is widely used because of the simplicity of testing. Burst strength is the result of a combination of many factors, depending amongst others on the amount and preparation of the fiber present. It is a useful indicator of strength property regardless of paper grade. The tearing resistance, which is a way of evaluating the crack sensitivity of the paper, is a strength dimension of central importance for all paper [Ek et al. 2009].

Initially, the significant differences were analysed between all the results of the strength properties measured, which were obtained for different l/w ratios and different Schopper-Riegler (SR) freeness numbers. The essential point for further studies is that the analysis of variance (table 1) showed that when all the studied strength properties (CMT, SCT, Burst and Tear) were tested together, they also differed significantly with regard to l/w ratio and SR freeness. The same statistics allowed an evaluation of the possible interaction between the studied technological parameters and analytical data e.g. l/w and SR freeness. Although, in relation to SCT values, the interaction was weaker than in the case of CMT, Burst and Tear, the analysis of variance proved that l/w and PFI refining (SR tests) together influenced the pulp's strength properties (table 1).

Table 1. Mean squares from the analysis of variance for CMT, SCT, Tear and Burst strength**Tabela 1. Średnie kwadraty z analizy wariancji dla oznaczeń CMT, SCT, oporu przedarcia i przepuklenia**

Source of variation Źródło zmienności	CMT CMT		SCT SCT		Burst Przepuklenie		Tear Przedarcie	
	df ss	ms śk	df ss	ms śk	df ss	ms śk	df ss	ms śk
l/w modul	4	962.4***	4	4.804***	4	9053***	4	88027***
SR SR	3	12497.1***	3	5.731***	3	167741***	3	144625***
l/w × SR modul × SR	12	1247.4***	12	0.342**	12	7315***	12	13670***
Residual Błąd	196	120.6	352	0.123	274	1164	79	2752

l/w – liquid-to-wood ratio

modul – modul cieczy warzelnej

SR – freeness in °SR (Schopper Riegler)

SR – smarność w stopniach °SR (Schopper Riegler)

df – degrees of freedom

ss – stopnie swobody

ms – mean squares

śk – średnie kwadraty

** – significant at 0.01 level

** – istotne na poziomie 0,01

*** – significant at 0.001 level

*** – istotne na poziomie 0,001

Table 2. The correlation matrix for CMT, SCT, Tear and Burst strength**Tabela 2. Macierz współczynników korelacji dla oznaczeń CMT, SCT, oporu przedarcia i przepuklenia**

Correlation Korelacje	CMT CMT	SCT SCT	Burst Przepuklenie	Tear Przedarcie
CMT CMT	1			
SCT SCT	0.538*	1		
Burst Przepuklenie	0.839***	0.665**	1	
Tear Przedarcie	-0.479*	-0.210	-0.549*	1

*,** or *** show increasing significance of correlation between analysed strength properties.

Minus before value indicates reverse correlation.

*,** lub *** oznaczają wzrastającą istotność korelacji pomiędzy analizowanymi właściwościami wytrzymałościowymi. Znak ujemny przed wartościami wskazuje korelację odwrotną.

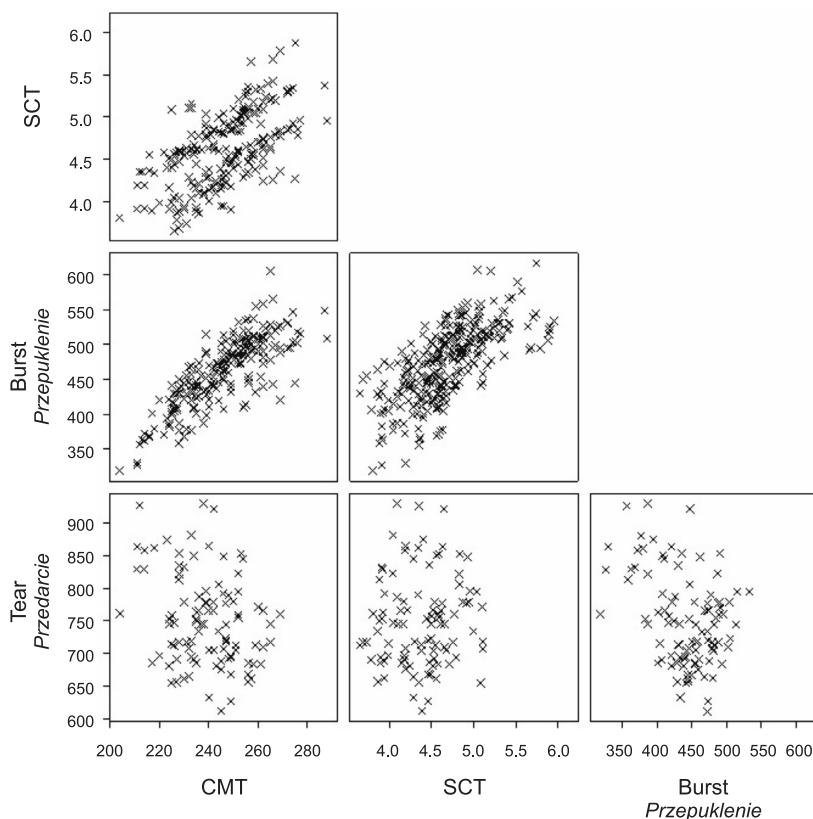


Fig. 1. Scatter plot matrix for CMT, SCT, Tear and Burst strength

Rys. 1. Wykresy rozproszenia dla oznaczeń CMT, SCT, oporu przedarcia i przepuklenia

In order to recognize more closely the mutual tendencies and interactions of the studied technological factors and pulp properties, correlations between the pairs of tested strength features (table 2, fig. 1) were analyzed. As seen in table 2 and on the scatter plot (fig. 1) the strongest correlation appeared between the CMT and Burst ($r = 0.839$). A weaker correlation showed SCT and Burst ($r = 0.665$). The less significant ($P < 0.05$) correlations were observed for SCT and CMT ($r = 0.538$), then Burst and Tear ($r = -0.549$) and at the end for SCT and Tear (the two last pairs showed negative correlations). The most important point is that in spite of the scattering data, a positive correlation between the increasing CMT, SCT and Burst values (fig. 1) is confirmed. The correlations were independent of the refining energy applied during sample preparation.

The pulp freeness is directly related to several processes that occur during refining such as external fibrillation, fiber shortening and fines creation. The other known result of refining is the internal fibrillation reflecting the increase in fiber swelling, which is caused by the delamination of cell walls and the general growth

of the capacity of pulp to retain water [El-Sharkawy et al. 2008]. During the next step significant differences were observed between the separate results of strength properties gained for the whole range of studied l/w ratios, and with regard to the increasing SR freeness numbers (table 3). The repeating letters (capital – for mean values) inserted according to the results of the pulp strength analysis prove the lack of significant differences. As could be expected, the CMT and SCT values generally increased with the higher SR numbers [Kim, Jo 2000]. Thus, refining in a PFI mill increased the tested paper sheet strength by influencing the surface area of the fibers allowing their optimum papermaking properties to develop. The mean values (calculated for all SR freeness range) of CMT showed significant differences between the 1.4 and 1.5 l/w ratios used.

Table 3. Mean values and coefficients of variation for CMT, SCT, Tear and Burst strength

Tabela 3. Wartości średnie i współczynniki zmienności dla CMT, SCT, oporu przedarcia i przepuklenia

CMT [N]									
CMT									
l/w modul	SR°								mean śr
	20		25		30		35		
	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	
1.4	227.9gh	3.85	249.3abcdef	5.63	250.9abcdef	2.58	252.7abcde	3.09	245.4B
1.5	247.2bcdef	6.45	253.2abcd	6.88	261.3abc	2.97	252.3abcde	2.15	253.8A
1.7	240.6defg	4.55	226.7gh	3.60	247.8abcdef	4.19	263.2ab	1.91	244.4B
1.8	223.3h	5.66	236.6efgh	3.58	253.9abcd	4.14	262.2ab	3.80	243.7B
2.2	235.4fgh	3.21	249.8abcdef	7.13	245cdef	5.09	264a	5.46	248.6AB
mean śr	231T		242.8S		251.7R		258.8P		
SCT [kN/m]									
SCT									
l/w modul	SR°								mean śr
	20		25		30		35		
	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	
1.4	4.426efg	6.42	4.691defg	8.71	4.96bcd	7.55	4.795cdef	8.28	4.72B
1.5	4.336fg	8.21	4.435efg	5.94	4.774cdef	6.30	4.715defg	5.05	4.575B
1.7	4.22g	8.95	4.413efg	8.24	4.677defg	6.14	4.89cde	4.55	4.542B
1.8	4.427efg	7.42	4.636defg	7.27	5.033abcd	8.61	5.078abcd	5.46	4.787B
2.2	4.857cdef	8.83	5.551a	6.41	5.245abc	7.32	5.42ab	6.85	5.26A
mean śr	4.452S		4.737R		4.965P		4.981P		
Burst [kPa]									
Przepuklenie									

Table 3. Continued
Tabela 3. Ciąg dalszy

l/w modul	SR ^o								mean śr
	20		25		30		35		
	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	
1.4	399h	5.36	467cdef	6.78	489.5abcde	6.10	515.8abc	6.17	468B
1.5	424.9fg	8.95	458.7def	4.67	490.7abcde	7.05	501.4abcd	4.36	470.4AB
1.7	478bcde	6.32	427.2fg	4.41	499.4abcd	7.19	529.6a	6.94	483.2AB
1.8	400.6g	11.81	452.6def	7.35	498.3abcd	7.82	519.6ab	7.36	466.8B
2.2	445.6efg	6.45	490.4abcde	5.97	515abc	8.86	523.4ab	8.14	493A
mean śr	422.4T		459.8S		497.7R		518.2P		
Tear [mN] Przedarcie									
l/w modul	SR ^o								mean śr
	20		25		30		35		
	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	mean śr	cv wz	
1.4	859.6a	4.25	802.7abc	9.79	749.7cdef	8.13	758.6bcde	7.77	792.4A
1.5	788.2abcd	5.24	682.7ef	2.38	694.2ef	7.10	676.2f	10.21	708.2C
1.7	720.8def	1.27	711.2def	3.75	715.8def	3.19	700.2ef	5.10	712.1C
1.8	801.1abc	9.79	712.8def	7.56	712.2def	8.23	757bcde	4.50	745.7BC
2.2	836.7ab	1.86	694ef	4.93	737.5cdef	7.84	736.7cdef	4.49	753.4B
mean śr	809.3P		732.4R		725.2R		736.2R		

l/w – liquid-to-wood ratio

l/w – modul cieczy warzelnej

SR – freeness in °SR (Schopper Riegler)

SR – smarność w stopniach °SR (Schopper Riegler)

abc... – repeated small letters show no significant difference between variables

abc... – powtarzające się małe litery wskazują na brak istotnych różnic pomiędzy zmiennymi

ABC... – repeated capitals show no significant difference between mean values of variables

ABC... – powtarzające się duże litery wskazują na brak istotnych różnic pomiędzy średnimi wartościami zmiennych

mean – mean value

śr – wartość średnia

cv – coefficient of variation

wz – współczynnik zmienności

In opposition to this, the average SCT values differed significantly at higher l/w ratios – between 1.8 and 2.2. Taking into consideration the preferences for aiming at high CMT pulp indices as seen in industrial practice, the results seem to show the possibility of pulping with a low l/w ratio. However, when plotting the analyzed data as a function of l/w ratio the same tendencies for these proper-

ties were not obtained (fig. 2). The SCT behaves in the same way, according to the increasing l/w. The other properties, only to some extent reflect this tendency (table 3). The plot of CMT is the worst (fig. 2). It is unknown which of many factors caused the fluctuations of the data, although it is supposed that cooking is the reason. It should be noticed that cooking in the vapour-gas phase at l/w ratio 1.6 does not assure the covering of the chips by the liquor. Different l/w ratios (from 1.4 up to 1.8) were used, and for that reason the results of analysis may fluctuate.

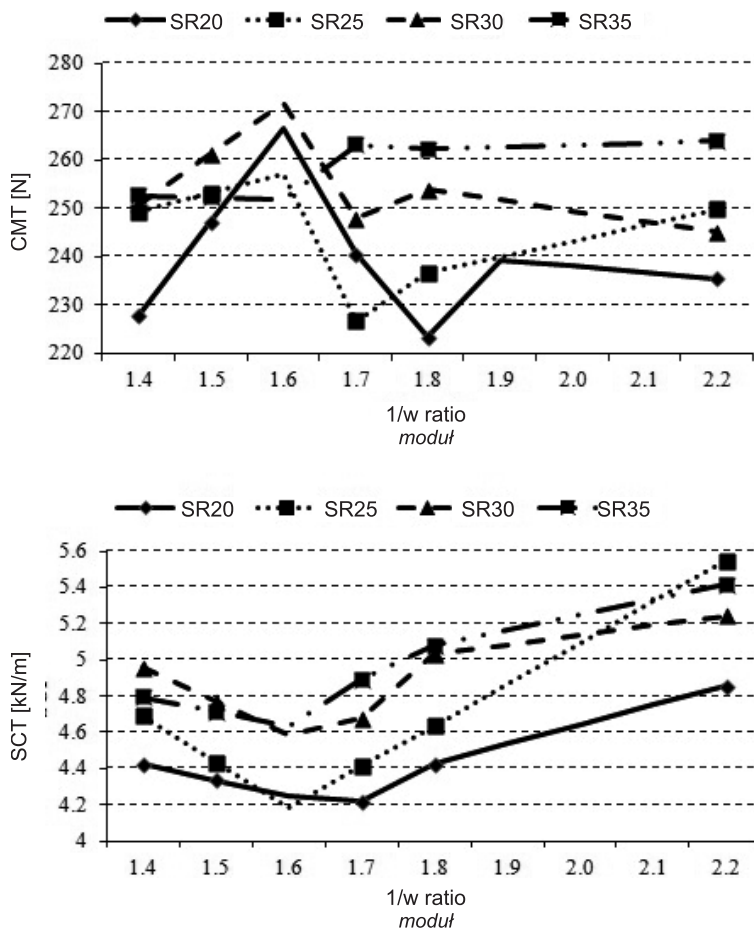


Fig. 2. CMT and SCT values as a function of l/w ratio
Rys.2. Wartości CMT i SCT w odniesieniu do zmian modułu cieczy warzelnej

The Burst results, increasing with higher SR freeness, showed similar tendencies as the SCT indices – significant differences were observed between 1.8 and 2.2 l/w ratios. Tear, in contrast, decreased when higher SR degrees were obtained. In this case, the LSD values of the mean results appeared for extreme l/w ratios:

1.4 versus 1.5 and 1.7 versus 2.2. The lowering of the Tear strength confirms well-known papermaking relations [Smook 1992]. Tear strength is a function of both the quantity of long fibers and inter-fiber bonding – when more fibers are cut a lower Tear strength is produced [El-Sharkawy et al. 2008].

The results of the statistical analysis of separate data inserted in table 3 (averages marked with small letters) showed a relatively small number of significantly differing results. Apart from the SCT values, more differences were observed for lower SR freeness – from 20°SR up to 25°SR. This can be explained by the known papermaking phenomena: on the one hand the increase of 5° SR freeness more at the beginning brings more fiber strength than at the end of refining. On the other hand, Burst, CMT and SCT indices generally grow with higher SR freeness, but at some specified point of refining they start to weaken [Markstrom 2005].

The tabular observation of pulp strength development tendencies (table 3) was difficult, thus in the next step, Principal Component Analysis (PCA) was carried out as a method facilitating the visual inspection of the obtained data sets. The PCA analysis made it possible to reduce the set of observations (all analyzed strength properties for 1.4, 1.5, 1.7, 1.8 and 2.2 l/w ratios and for all SR freeness) and to answer the question regarding which l/w and SR freeness values formed a similar data collection. The PCA was performed with the use of the mean values because we had at our disposal the different number of readings for all studied properties (CMT, SCT, Burst and Tear). Fig. 3 represents the visualization of the researched coordinates in a two-dimensional data space. The most important features that influenced this arrangement of points are CMT, SCT, Burst and Tear strength. Only 0.92% of the primary data (100% - 78.17% - 20.91%) was lost after a transformation from the four-dimensional space to the two-dimensional plane, therefore the observed arrangement of data may be treated as almost original. As seen in fig. 3 five similar groups of points representing different l/w and SR freeness can be distinguished. The visualization shows that the results (combination of l/w and SR freeness) group together according to higher l/w ratios and in this case the SR freeness does not significantly differentiate the pulp as regards strength properties. When lower l/w ratios were used (e.g. 1.4), the SR degrees, in contrast, differentiated strongly the strength properties and that is why the combination of l/w and SR freeness appears separately. However, we can already distinguish two similar groups of l/w and SR freeness: 1.5/35°, 1.5/30° and 1.5/20°, 1.5/25° for l/w 1.5. It should be mentioned that similarities between the analyzed data pairs (l/w and freeness) along the OX axis (first principal component) are weaker than along the OY axis (second principal component). Taking that into consideration, as seen in fig. 3, l/w ratios 1.4 and 1.5 – the lowest ones used during the experiment – differentiated the most importantly pulp strength properties, independently of the SR freeness values. The results of the PCA analysis suggest that pulp produced at the lower l/w ratios would need special care during refining assuring optimal papermaking properties.

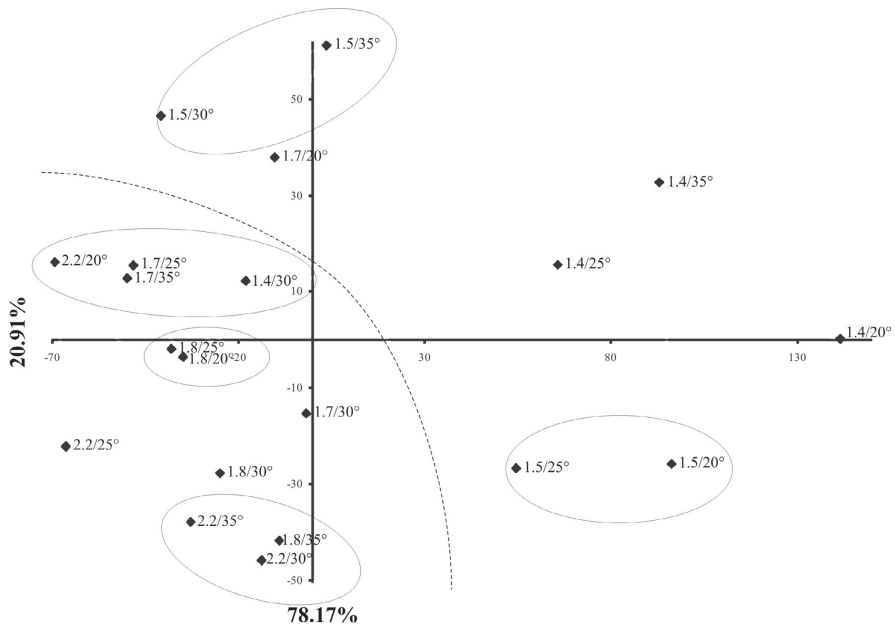


Fig. 3. Confirmation of combinations of liquid-to-wood ratio stages and SR freeness in the space of two principal components for CMT, SCT, Tear and Burst strength
Rys.3. Potwierdzenie kombinacji modułów cieczy warzelnej i smarności masy w przestrzeni dwóch głównych składowych dla oznaczeń CMT, SCT, oporu przedarcia i przepuklenia

Parallel coordinate plots (PCPs) are an efficient tool for visualizing multivariate data [Inselberg 1985; Wegman 1990]. PCPs can be a very useful tool for the selection of interesting (the best) combinations of liquid-to-wood ratios and SR degrees in the case of many attributes of interest.

The most important application of the tested NSSC pulp is the production of the corrugated medium, and that is why there was a focus on the analysis of CMT and SCT indices. $CMT = SCT_{md} \times 60(N)$, approaching the correlation between CMT and SCT measured along paper machine direction (md) [Markstrom 2005] is a well-known formula. Generally, pulp's CMT and SCT indices should increase simultaneously with higher SR numbers. The PCPs analysis made it possible to observe the tendency of the CMT and SCT development caused by the l/w changes. Fig. 4 shows PCP for 20 objects (combinations of l/w and SR freeness) and four properties (CMT, SCT, Burst and Tear). The reciprocal orientation of breaking lines confirms or excludes the correlation between the neighboring variables. The orientation close to parallel and with a similar angle of inclination, representing the position of CMT on the plot higher than SCT, indicates a correlation that was marked as "positive". The crossing lines show a "negative" correlation among the variables. As seen in fig. 4, 13 positive correlations between CMT and SCT can be distinguished, concerning nearly the whole range of l/w and SR freeness.

eness combinations used for analysis. Apart from one combination of l/w and SR freeness (2.2/35° respectively), negative correlations appeared rather for the lower SR freeness numbers (between 20°SR and 25°SR) and/or for the highest value of liquor-to-wood ratio used during cooking i.e. 2.2 (table 4).

Table 4. Positive and negative correlations between CMT and SCT values – Parallel coordinate plot analysis

Tabela 4. Pozytywne i negatywne korelacje pomiędzy wartościami oznaczeń CMT i SCT - wykres współrzędnych równoległych

Positive correlations <i>Korelacje pozytywne</i>	Negative correlations <i>Korelacje negatywne</i>
Liquor to solid ratio/SR° freenes <i>Moduł/smarność SR°</i>	
2.2/35°, 1.7/35°, 1.8/35°, 1.5/30°, 1.8/30°, 1.5/25°, 1.4/35°, 1.5/35°, 1.4/30°, 1.4/25°, 1.7/30°, 1.5/20°, 1.7/20°	2.2/25°, 2.2/30°, 1.8/25°, 2.2/20°, 1.4/20°, 1.7/25°, 1.8/20°

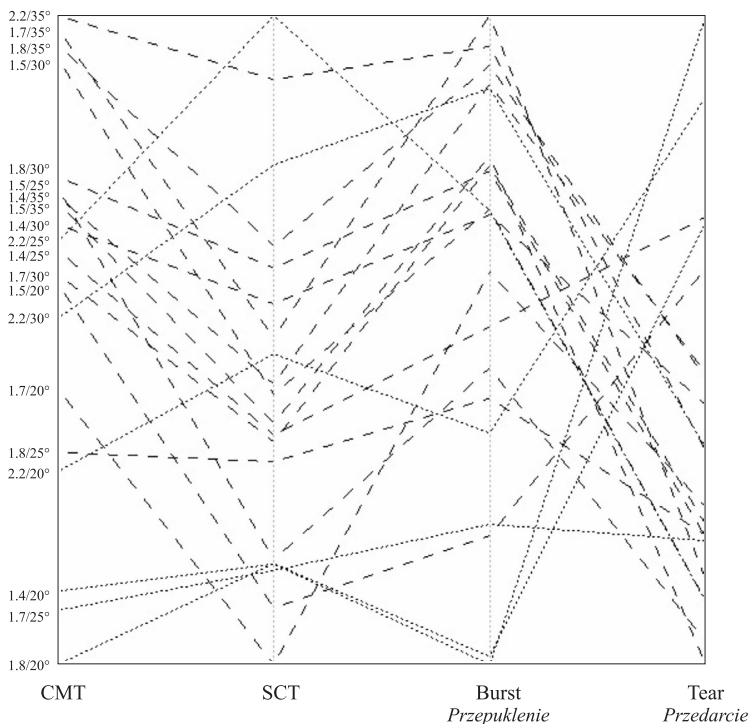


Fig. 4. Parallel coordinate plot for 20 objects (combinations of liquid-to-wood ratio stages and SR freeness) and four traits (CMT, SCT, Burst and Tear strength)

Rys.4. Wykresy współrzędnych równoległych dla 20 analizowanych obiektów (kombinacje modułów cieczy warzelnej i smarności masy) i czterech cech (CMT, SCT, przepuklenie i opór przedarcia)

The visualization shows that the best pulp strength properties (CMT, SCT and Burst) were gained for the combination of l/w and SR freeness – 2.2/35°. However, the rest of the results obtained at the highest l/w (2.2) indicating a negative correlation with the combination mentioned above, (2.2/35°), suggests that pulps obtained at such cooking conditions may present unpredictable strength properties. Besides the highly refined pulps (1.7/35°SR and 1.8/35°SR) that will be discussed below, the next combination representing high CMT values is 1.5/30°SR and then 1.8/30°SR. Although the pulp obtained after cooking at 1.8 l/w showed better SCT and B values as compared to those processed at 1.5 l/w (all refined to 30°SR), the latter ones showed better correlations between the neighboring variables. As opposed to 1.8 l/w, PCPs analysis for 1.5 l/w shows that all lines were relatively parallel and with a similar angle of inclination. Thus, cooking at such a low liquor-to-wood ratio makes it possible to produce the pulp not only with good but also predictable strength properties and may be implemented in industrial practice.

The other question, relating to the results of statistical analysis presented above, is the choice of appropriate l/w values and the evaluation of the SR number influence for further studies (time, temperature). Birch pulp refined above the 30° SR brings a less dynamic strength property increase. To reach better tensile stiffness, it is necessary to involve too much refining energy [Lumiainen 2000]. Applied to high specific energy consumption (SEC) the refining process makes paper less competitive from the cost point of view [Lumiainen 2000]. Higher energy consumption is not proportionally transferred into gains in SCT, CMT or Burst strength. Although high SR freeness (for example, 35°SR) positively influences fiber swelling, it also causes worse dewatering on the wet end of the paper machine and consequently worse paper web dryness after the wire and press section [Smook 1992; Lumiainen 2000]. Although, for further studies the same range of SR freeness (pulp samples refined up to 35°SR) was chosen, at the same time at 30°SR the best CMT, SCT and Burst strength developments were obtained for pulp processing at 1.5 and 1.8 l/w ratio respectively (fig. 4), and these liquor-to-solid ratios were used during further research concerning the influence of time and cooking temperature on papermaking NSSC pulp properties.

Conclusions

1. Using a set of three statistical methods (analysis of variance, parallel coordinates, principal components analysis) it was shown that by having a sufficiently large database it is possible to evaluate industrial scale technological factors varying in extremely narrow ranges of values.
2. When applying statistical methods it has been proved that when the liquor-to-wood ratio 1.5 is used during cooking, it is possible to obtain NSSC pulp with strength properties comparable to those processed at higher liquor volumes.

Saving the liquor, and consequently limiting inorganic to organic ratio in spent liquors, may be beneficial for its further treatment and/or recovery.

Acknowledgement

The research paper was financed by The European Social Fund within the framework of The Integrated Program of the Regional Development Process.

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List of standards

- EN/ISO 9895:2002** Paper and board – Compressive strength – Short span test
- EN 21974:2002** Paper – Determination of tearing resistance (Elmendorf method)
- EN/ISO 2758:2005** Paper – Determination of bursting strength
- EN/ISO 7263:2008** Corrugating medium – Determination of the flat crush resistance after laboratory fluting
- SCAN–CM–40:01:2001** Wood chips for pulp production – Size distribution. Scandinavian Pulp, Paper and Board Testing Committee

WPLYW ZMIENNYCH CZYNNIKÓW PROCESOWYCH NA WŁAŚCIWOŚCI WYTRZYMAŁOŚCIOWE BRZOWYCH MAS PÓLCHEMICZNYCH (NSSC). W KIERUNKU GRANIC OPTIMALIZACJI: CZĘŚĆ PIERWSZA – WPLYW MODUŁU CIECZY WARZELNEJ

Streszczenie

Celem pracy było ustalenie warunków obojętnosiarczynowego roztwarzania drewna brzozonego i otrzymywania mas półchemicznych (NSSC) o możliwie najwyższych właściwościach wytrzymałościowych, przy wykorzystaniu możliwie najniższych wartości czynników procesowych: modułu cieczy warzelnej, temperatury i czasu warzenia. Badania oparto na granicznych (minimalnych i maksymalnych) wartościach zmiennych niezależnych procesu roztwarzania drewna prowadzonego w warunkach przemysłowych. Analizowano następujące zmienne: czas warzenia (od 13 do 15,5 min), temperaturę warzenia (od 172 do 179°C) i moduł cieczy warzelnej (od 1,2 do 2,2). Pomimo bardzo wąskich zakresów kontroli zmiennych procesu roztwarzania, połączenie obszernej bazy danych i zestawu metod analizy statystycznej (analiza wariancji, analiza współrzędnych równoległych, analiza składowych głównych) pozwoliło na wyznaczenie optymalnych zakre-

sów badanych czynników technologicznych determinujących testowane właściwości wytrzymałościowe mas włóknistych. Analizy statystyczne wykazały, że zmienne niezależne wpływały na poziom wartości badanych wskaźników wytrzymałościowych: CMT, SCT, oporu przedarcia i do pewnego stopnia również przepuklenia. Obniżając moduł cieczy warzelnej do 1,5, uzyskano masy włókniste o porównywalnych właściwościach wytrzymałościowych do mas warzonych przy wyższych modułach. Ograniczenie ilości dozowanego ługu warzelnego, a zatem możliwość zmniejszenia udziału substancji nieorganicznych do organicznych w ługu powarzelnym, może być korzystne z ekonomicznego punktu widzenia oraz dalszego przerobu ługu powarzelnego.

Słowa kluczowe: NSSC, masa obojętnosiarczynowa, moduł cieczy warzelnej, metody statystyczne