Comparison of the Beatability for Fast-growing Plants, Softwood, and Hardwood Sources of Fibers

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Refining is a primary unit operation that has a large impact on the quality of paper products and cost of production. The refining process of cellulose fibers is the most energy-intensive step in the preparation of paper pulp. High energy consumption during the refining process has motivated researchers to improve the economics of the process without decreasing the strength of the paper produced. This objective can be realized through easily refined pulps that are produced from alternative vegetal fibrous raw materials. This work compares the energy consumption of refining soft, hardwood, and fast-growing fibrous materials to 30 °SR. The goal was to reduce energy consumption while maintaining the strength properties of the paper received. For this purpose, cellulose pulps from fast growing plants including poplar, larch, and grasses were used.

Keywords: Refining; Energy consumption; Strength properties; Alternative fibrous materials

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INTRODUCTION

The technology of papermaking includes a series of processes, most of which have high energy requirements. The costs and availability of energy supply and climate change are important factors that will decide the future of energy-intensive industries including the paper industry. Therefore, many research programs relating to energy savings in the paper industry have been launched in recent years (El-Sharkawy *et al.* 2008; Michniewicz and Janiga 2011; Kerekes 2014).

The refining process of cellulose fibers is one of the most energy-consuming stages of papermaking. In currently used refiners, the energy efficiency is extremely low and not exceeding 30% (Atalla and Wahren 1980; Koskenhely 2007). Consequently, specific energy consumption in the pulp refining process is approximately 100 to 500 kWh/t (Heymer 2009; Kerekes 2010), which represents around half of the total electric energy consumption in a paper mill (Arjas 1980; Scheihing 2005; Wang *et al.* 2005). Specific energy consumption of up to 15 kWh/MT/°SR is not uncommon. The refining process is extremely important and not only because of the paper production costs. Changes in refining pulp have a crucial impact on the paper properties (Zeng *et al.* 2012; Joutsimo and Asikainen 2013; Vishtal and Retulainen 2014). The high energy consumption during the refining process has motivated researchers to improve economics of the process without loss of strength of the paper, all while reducing direct and indirect environmental effects.

The main cause of low energy efficiency of refining is maladjustments of existing refiners to the properties of currently used pulps. To adapt the refiners to processing of primary and secondary fibers, it is necessary to change the operation principles. Conventional refining has been replaced by unconventional methods of fibre treatment such as ultrasound (Tatsumi *et al.* 2000; Manfredi *et al.* 2013), enzymes (Gil *et al.* 2009; Cui *et al.* 2015), steam explosion, pressure fluctuation, low temperature treatment (Young 1980; Bajpai 2005), and cavitation (Shankar *et al.* 2018). Unfortunately, none of these methods have brought any crucial progress in this field (Przybysz and Przybysz 2013). One of the ways of reducing refining energy is to use alternative, easy to refine vegetal fibrous raw materials in papermaking (the fast growing trees and grasses).

Especially attractive for the paper industry are fast growing trees and grasses that are adapted to the European moderate climate, such as tall fescue and switchgrass. Production of paper products from these resources have been increasing (Zalesny *et al.* 2011).

Grass biomass has the potential to exceed the productivity of other materials, *e.g.* wood from forests, because it can be harvested every year. This makes it possible to reduce the demand for wood and avert destruction of forests (Leblois *et al.* 2017). The non-wood seeding ensures productive crops for a few or even more than 10 years (80 to 150 tons/ha) at relatively low costs (Coffey *et al.* 1997). Moreover, plantations of such plants may be situated in areas that cannot be used for production of food because of ecological and economic reasons (Martyniak and Żurek 2014).

The objective of this work was to compare the beatability of two fast-growing trees, such as of poplar hybrid clone 275 and European larch and two grasses such as tall fescue and switchgrass as materials for papermaking. Properties of pulps derived from these plants were compared with properties of pulps obtained from three materials that are used in papermaking such as pine and birch wood and miscanthus biomass. The studies have been conducted for unbleached and bleached samples.

EXPERIMENTAL

Raw Materials

Grasses (*Festuca arundinacea, Panicum virgatum,* and *Miscanthus giganteus*) were harvested using a reel lawn mower ALKO 5001 R-II (AL-KO, Kötz, Germany), in the generative (blooming) phase. The biomass was dried to the humidity of 10% and chopped to 1.5 to 2.0 cm chaff using a MTD 475 petrol powered shredder (Briggs & Stratton, Viernheim, Germany), dedicated for disintegration of tree branches.

The following wood materials were selected for research: poplar cultivar 'Hybrid 275', European larch (*Larix decidua* Mill.), pine (*Pinus sylvestris* L.), and birch (*Betula pendula* Roth). Woodchips were obtained from trunks with a diameter of around 25 cm. Before pulping, wood was manually debarked and deprived of knots. Wood logs were sawn using an electric Milwaukee MD 304 saw (Milwaukee, Brookfield, Germany) to 25 mm slices and chopped manually to 25 x 16 x 8 mm chips. Materials used in the tests were obtained from plantations managed by State Forests National Forest Holding.

Cellulosic Pulps

Cellulosic pulp from woodchips and grasses were prepared by the sulfate (kraft) pulping method. Pulping conditions were established within the frames of the research project PBS1/A8/16/2013. Pulping processes were conducted in a 15 dm^3 stainless laboratory digester PD-114 (Danex, Katowice, Poland) with temperature regulation (water jacket) and agitation (3 swings per minute, swinging angle of 60°). Cooking liquid was prepared according to Modrzejewski *et al.* (1985). The addition of active alkali was 26%

(260 g per batch) and water to wood ratio (v : w) was 4 for wood and 10 for grasses. The dry weight (DW) of all materials was determined before pulping. Wood (1000 g DW) and grass (500 g DW) samples were suspended in alkaline sulfate solution and heated. The maximal digestion temperature was 165 °C for hardwood and grasses and 172 °C for softwood. Heating time was 120 min, and cooking at maximal temperature also lasted for 120 min. The temperature was decreased to 22 + 10 °C using cold tap water. After delignification, the material was washed several times with demineralized water and incubated overnight in demineralized water to remove residues of the alkali-soluble fractions. The solids were disintegrated in a laboratory JAC SHPD28D propeller pulp disintegrator (Danex) at 12000 revolutions, and the fibers were screened using a membrane screener PS-114 (Danex) equipped with 0.2 mm gap screen. The pulp was dried at ambient temperature for 48 h. The humidity of air-dried pulp was 5% to 6%. Kappa numbers were examined for dried pulps (this is an indication of the lignin content in pulp), according to ISO 302 (2015). The average polymerization degree of cellulose contained in the pulps was determined by the viscometric method in compliance with Standard ISO 5351 (2010). Pulps were kept in hermetic vials before further processing.

Bleaching of Pulps

The peroxide bleaching phase was conducted using bleach liquor consisting of: 3% H_2O_2, 2.5% NaOH, 0.2% $MgSO_4$ and 1% Na_2SiO_3 (o.d. basis). The pulp (20 g o.d.) and the bleaching reagents were blended with distilled water in a glass bottle to obtain a final consistency of 10%, immersed in a water bath (LaboPlay, Bytom, Poland), held at 80 °C for 3 h and manually mixed at 30 min intervals. At the end of the treatment, the pulp was discharged, filtered, washed with four aliquots of 1000 mL distilled warm water, dried and stored in a plastic bag for further treatment.

Refining of Pulps

Before processing, pulp was soaked in water for 24 h. Then, cellulosic pulps were treated in a laboratory Danex JAC SHPD28D propeller pulp disintegrator, according to PN EN ISO 5263-1 (2006) at 23000 revolutions. Cellulosic pulps were refined to 30 ± 1 °SR. The process of refining was performed in Danex JAC PFID12X PFI mill in which a single batch was 22.5 g of dry pulp, according to PN-EN ISO 5264-2 (2011). The time of refining to 30 °SR was the same for the unbleached and bleached pulps.

After each refining, the properties of pulp were evaluated. Schopper-Riegler freeness was used to the ability of the pulp to dehydrate under standard conditions. The Schopper-Riegler freeness was measured using Schopper-Riegler apparatus (Thwing-Albert Instrument Company, West Berlin, USA), according to PN-EN ISO 5267-1 (2002).

Paper Sheets

The next step was forming sheets of paper in the Rapid-Koethen apparatus. The formation of paper sheets was performed in accordance with PN-EN ISO 5269-2 (2007). Each laboratory paper sheet was described by basis weight of 80 g/m². Only sheets with a base weight that ranged from 79 to 81 g/m² were accepted for further investigation. Test sheets were conditioned for 24 h at 23 ± 1°C and 50 ± 2% relative humidity, according to ISO 187 (1990). The paper properties were examined as follows. The tear index was determined according to ISO 1974 (2012). Mechanical measurements were performed on a Zwick Roell Z005 TN ProLine tensile testing machine (Ulm, Germany), according to PN-EN ISO 1924-2 (2010):

- I_B – breaking length [m];
- σ_T^b – width related force with break [N/m];
- σ_T^W – force at break index [Nm/g];
- ε_T – yield strain [%];
- W_T^b – work absorption [J/m^2];
- W_T^W – work absorption index [J/g];
- E^b – tensile stiffness [N/m];
- E^w – tensile stiffness index [Nm/g];
- E^* – Young's modulus [MPa];
- F_{low} – being of Young's modulus [N];
- F_B – tensile force at break [N].

RESULTS AND DISCUSSION

All fibrous materials were transformed to cellulosic pulps at the same concentration of bases (of 26% on a wood dry weight). Therefore, the value of the kappa number corresponded to the residual lignin content and showed their receptivity to pulping. As shown in in Table 1, the pulps made from grasses were characterized by significantly lower kappa numbers compared with the pulps made from hardwoods and softwoods. The European larch wood was the least susceptible to pulping. The kappa number of the pulp derived from the larch wood was the highest at 56.8 (Table 1). Following the bleaching process, the index decreased by about 25 ÷ 80% based on the raw material type (Table 1).

The degree of polymerization of grasses ranged between 1640 and 1663. The DP of cellulose was significantly higher for the annual plants samples versus the wood pulps DP (1180 ÷ 1500). After bleaching process, dependent on the type of pulp, the DP of cellulose fell by 14 ÷ 33% (Table 1).

Table 1. Properties of Examined Pulps

Pulp	Time of Refining to 30 °SR (s)	Kappa Number (-)		Degree of polymerization (-)	
	Unbleached and bleached pulp	Unbleached pulp	Bleached pulp	Unbleached pulp	Bleached pulp
Miscanthus	20	14.31 (0.16)	7.32 (0.06)	1649 (3.16)	1302 (3.69)
Tall fescue	12	12.71 (0.19)	8.55 (0.17)	1663 (3.58)	1364 (3.22)
Switchgrass	20	13.71 (0.08)	8.38 (0.01)	1640 (0.21)	1414 (0.00)
Hybrid 275	90	20.63 (0.15)	15.48 (0.18)	1500 (0.08)	1009 (0.00)
Birch	120	23.38 (0.21)	12.21 (0.12)	1322 (2.64)	1068 (1.22)
Larch	200	56.83 (0.31)	39.1 (0.10)	1235 (3.81)	1012 (3.73)
Pine	120	42.22 (0.13)	8.59 (0.08)	1180 (2.05)	906 (2.11)

Note: Standard deviation are given in brackets.

Figure 1 compares the beatability of papers made from investigated pulps. Tall fescue achieved 30 °SR in the shortest time (12 s). Beatability of Hybrid 275 was comparable with the beatability of materials that are used in papermaking (pine and birch wood). Larch was hard to refine; the 30 °SR was achieved in 200 s.

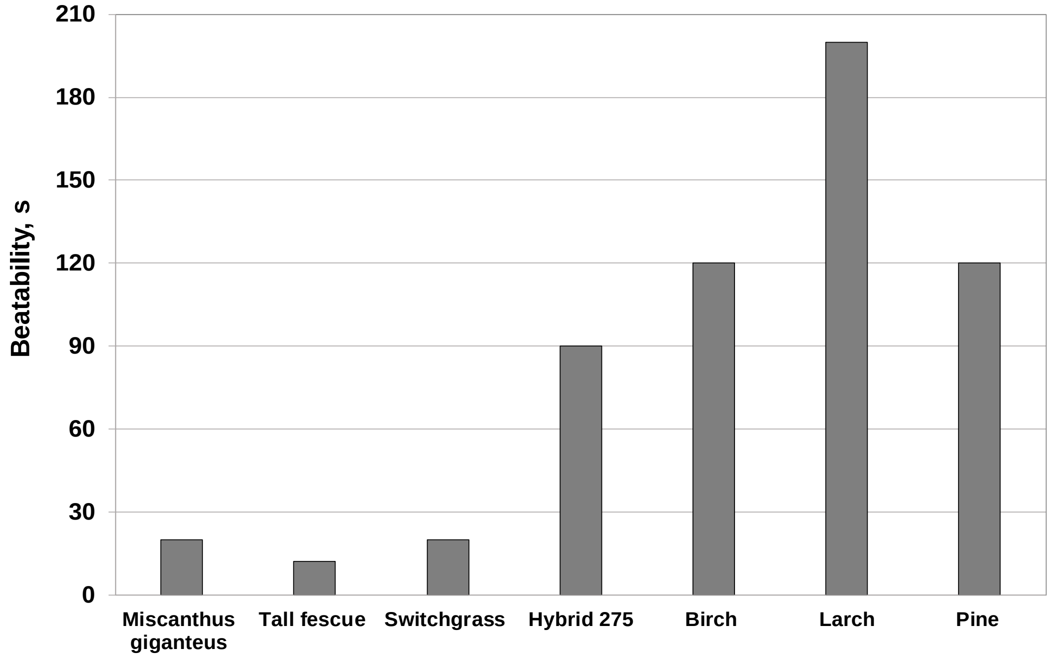

Fig. 1. Beatability of papers received from examined pulps after refining to 30° SR

Table 2 shows the mechanical properties of papers made from the investigated unbleached pulps, including the breaking length. The indicator is one of the fundamental static tensile properties of paper. Papers made from grasses exhibited good results. The refining time to 30 °SR was low (12 ÷ 20 s), but the breaking length was satisfactory (4800 ÷ 6050 m). Hybrid 275 achieved the relatively high level of breaking length (7750 m), although it was a comparatively short time of refining (90 s). Also, the values of larch mechanical properties were high (7800 m); however, the time of refining was long (200 s). From an economic point of view, larch is much less attractive despite the high length of fibers. For the other examined properties, the same relationship was observed (Table 2).

Table 2. Properties of Papers (unbleached pulps)

Pulp	σ_T^b	σ_T^W	ε_T	W_T^b	W_T^W	E^b	E^w	E^*	F_{low}	F_B	l_B	Tear index
	N/m	Nm/g	%	J/m^2	J/g	N/m	Nm/g	MPa	N	N	m	mN·m^2/g
Miscanthus	4720	59.6	2.0	63.6	0.803	538000	6800	4890	3.51	69.6	6050	2.7
Tall fescue	4460	54.1	2.2	70.6	0.858	512000	6220	4660	3.30	65.5	5500	3.8
Switchgrass	3840	47.2	2.4	62.2	0.765	456000	5610	4140	2.94	56.6	4800	2.8
Hybrid 275	6350	76.2	4.4	196	2.36	558000	6700	5070	3.50	93.9	7750	3.4
Birch	7000	85.5	2.9	130	1.61	635000	7780	5770	3.70	103	8700	3.0
Larch	6440	76.7	3.7	160	1.90	565000	6730	5140	3.64	93.9	7800	6.7
Pine	7010	85.9	2.9	133	1.63	636000	7790	5780	3.80	105	8750	6.2

Table 2 also shows a comparison of paper tear index values. The larch paper achieved the highest value (6.7 mN·m^2/g). However, this does not change the fact that time of refining was relatively long to achieve this value. The tear resistance of Hybrid 275 and grasses was comparable to the tear resistance of hardwood.

Mechanical properties of papers produced from bleached pulps are shown in Table 3. The bleaching process of pulps did not show significant effects relative to the strength properties of paper. It is a difficult to give a direct correlations and conclusions in relation to the unbleached samples. The explanation of the reasons for this fact is complicated by the fact that presented annual plants are a new fibrous raw material and the grasses have not been tested in this direction until now. For this reason, these values cannot be compared to literature data.

Table 3. Properties of Papers (bleached pulps)

Pulp	σ_T^b	σ_T^W	ε_T	W_T^b	W_T^W	E^b	E^w	E^*	F_{low}	F_B	l_B	Tear index
	N/m	Nm/g	%	J/m^2	J/g	N/m	Nm/g	MPa	N	N	m	mN·m^2/g
Miscanthus	4840	60.6	2.4	82.7	1.04	532000	6660	4830	3.57	72.3	6200	1.9
Tall fescue	4600	57.0	2.6	85.8	1.06	506000	6270	4600	3.06	68.1	5800	1.3
Switchgrass	3380	42.5	2.4	57.4	0.723	417000	5260	3790	2.71	49.8	4350	1.4
Hybrid 275	5230	65.5	4.4	170	2.13	497000	6230	4520	3.32	77.8	6700	1.5
Birch	6900	84.9	2.9	131	1.65	641000	7810	5800	3.59	102	8600	1.2
Larch	7120	86.8	3.4	164	1.99	640000	7800	5820	4.51	105	8850	5.5
Pine	7000	85.2	3.0	141	1.71	642000	7810	5830	3.64	103	8700	4.9

For economic reasons, the results suggest that tall fescue, miscanthus, and poplar hybrid 275 are the most attractive materials to replace birch wood in papermaking. The biomass of fast-growing plants may be regarded a profitable and technologically attractive alternative due to the limited resources of birch wood (Koski and Rousi 2005; Soleimani *et al.* 2012). The alternative fiber resources may be used to manufacture kraft and semi-chemical pulps (Cappelletto *et al.* 2000). Properties of the pulps obtained from grasses and birch wood are similar (Thykesson *et al.* 1998). However, they are worse than those of pine and larch wood pulps, which are characterized by the higher fiber length. Softwoods require a longer refining time, so they are not attractive for economic reasons.

Although these experiments were preliminary. The results obtained encourage the continued search for relatively easy to refine pulps produced from alternative vegetal fibrous raw materials. It is particularly important for the paper industry because there has been no significant progress in pulp refining process since the mid-20th century.

CONCLUSIONS

1. Grasses were the most promising of the tested materials from the point of view of reducing energy in the refining process. Even though the refining time of grasses was short, the strength properties of the resulting papers were satisfactory.
2. The properties of the fast growing poplar (Hybrid 275) did not show significant differences compared to hard and softwood.
3. The pulps produced from fast growing poplar and grasses are interesting substitutes for hardwood pulps. These fiber resources are attractive from the technological and especially economic points of view because of the short period of growth and productive crops.

4. Larch raw material is hard to refine, so it does not reduce energy consumption in the refining process.

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