Role of External Fibrillation in High-consistency Pulp Refining

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The mechanical and hydrodynamic phenomena occurring in the refining zones of disc refiners cause fibres to undergo fibrillation. This paper presents a study of the changes occurring during fibre fibrillation as expressed in terms of the fibrillation index when refining pulp with a 10%, 15%, and 20% consistency. The influences of the tangential force of a circular bar and a straight bar on fibre fibrillation were compared. The changes in the tangential force are shown to depend on the angle between the tangent to the cutting edge and the radius from the centre of the disk to the tangency point. Increasing the angle between the tangent to the cutting edge and the radius from the centre of the disk to the tangency point gives higher fibrillation index values. The study revealed a relationship between fibre fibrillation and the strength characteristics of handsheets.

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INTRODUCTION

Pulp refining results in the internal and external fibrillation of fibres. External fibrillation separates cell membranes and fibrils from fibres, which increases the outer surface of the fibres and the number of free hydroxyl groups on their surface. The outer specific surface of the fibres increases (Mohlin 1989; Kang and Paulapuro 2006; Fernando 2007; Backstrom *et al.* 2012). Internal fibrillation irreversibly rearranges the structural elements of the secondary wall of the fibres without reducing their strength, while increasing their flexibility and plasticity (Hartman 1984; Wang *et al.* 2007; Lebedev *et al.* 2018; Przybysz *et al.* 2020; Penkin and Kazakov 2022).

The positive impact on the quality of paper products and the economic benefits of increasing the consistency of the pulp during refining have been repeatedly discussed in various literature (Alashkevich *et al.* 2006; Muhic 2008; Olejnik 2013; Kerekes 2015; Chen *et al.* 2016). Most modern paper and pulp mills now widely use disc refiners in low-consistency (1% to 4%) pulp refining. High-consistency (5% and above) pulp refining appears to be a promising method of improving the strength characteristics of paper sheets. High-consistency pulp refining increases the thickness of the fibrous layer between the refining surfaces of the rotor and stator discs, making the fibres undergo less cutting and increasing the inter-fibre frictional forces (Henderson *et al*. 1965).

As the inter-fibre friction intensifies, the internal and external fibre fibrillation grade increases and the fibre shortening grade decreases (Lebedev *et al.* 2018; Penkin and Kazakov 2022). This is especially important in bag and packaging paper production, as these types of paper are required to have high strength characteristics (Hill *et al.* 1950; West 1964; Henderson *et al*. 1965; Herbert *et al.* 1967; Jackson 1967; Leask 1967; Carlson 1981; Karnis 1989; Pagliarini 1992).

Researchers in pulp refining have demonstrated that internal fibrillation plays an important role in the preparation of fibres for interfibre bond formation and their ability to bind together into strong paper sheets (Paavilainen 1993; Fernando *et al.* 2011, 2012; Przybysz *et al.* 2020).

The phenomena of fibre external and internal fibrillation during pulp refining are hard to distinguish, as they are closely interconnected, technically occur simultaneously, and are supposed to equally influence the strength characteristics of the paper sheet (Claudio-da-Silva 1983; Wang *et al.* 2007; Hartman 1984; Abitz and Luner 1989; Mohlin 1989). Fibrils in the fibres that are produced by external fibrillation fulfil the role of short-fibre fractions and give paper sheets certain strength characteristics during their production (Szwarcztajn and Przybysz 1972; Kang and Paulapuro 2004).

Advances in high-precision scanning electron microscopy and its widespread use in the analysis of the morphological structure of refined pulp (Fernando and Daniel 2004; Kurhila 2005; Liu *et al.* 2020) now allow qualitatively evaluating the degree of fibrillation and, particularly, external fibrillation of fibre.

Many researchers studying the structural modification of fibres in external fibrillation claim that the nature of the phenomenon primarily depends on the parameters of the refining process (Kang and Paulapuro 2006; Fernando 2007). However, most of the data are based on the results of low-consistency pulp refining (under 5%) (Kang and Paulapuro 2006).

The most important feature of high-consistency pulp refining is the extensive development of external fibrillation of fibres, which is more critical than during low-consistency pulp refining. This phenomenon is associated with the high uniformity of fibre processing due to interfibre friction, which in this case is the main type of influence exerted on the pulp (Rosenfeld and Hofmann 1965; Dean 1995; Kerekes and Schell 1995; Kerekes 2015; Kerekes and McDonald 2018).

Until today, studies of the phenomena associated with external fibrillation of fibres in high-consistency pulp refining have mainly focused on the interaction of fibres with each other, with few studies devoted to the effect of refiner plates on the intensity of external fibrillation.

Different manufacturers (Andritz, Voith) have designed a wide range of bar plates to refine high-consistency pulp. The structural design of refiner plates plays an important role in high-consistency pulp refining in ensuring a certain degree of external fibre fibrillation. The efficiency of using such bar plates in pulp and paper mills is associated with the production of sack paper with high tensile energy absorption (TEA) and a decrease in specific refining energy consumption (West 1964; Henderson *et al*. 1965; Herbert *et al.* 1967; Jackson 1967; Leask 1967; Pagliarini 1992). The objective of this research is to study the role of external fibre fibrillation in providing the strength characteristics of handsheets during high-consistency pulp refining in terms of the structural and strength properties of the refiner plates.

EXPERIMENTAL

Methods and Materials

Circular and straight bar angles

The change in the morphological properties of pulp during refining depends on various factors that should be taken into account. The tangential force occurring on the cutting edges of bar plates is one of the factors giving rise to the fibrillating effect on fibres (Kovalev 2007; Alashkevich *et al.* 2010). The tangential force is affected by the bar angle β_x (Vasil'ev 1983; Lundin *et al.* 1999; Elahimehr *et al.* 2015). The bar angle β_x is formed between the tangent t - $t^{A,}$ and the radius r_x from the centre of the disc of point O to the point of contact A, as shown in Fig. 1 (a) and (b). In this work, the change in the angle of the circular and straight bars was studied. A distinctive feature of circular bars is the uniform increase in the angle β_x along the entire contact line of the cutting edge to the angle β'_x (Kovalev 2007; Alashkevich *et al.* 2021). Straight bars are notable for an opposite trend associated with a decrease in the angle β_x to β'_x along the entire contact line of the cutting edge from the inlet to the circular bar cavity *1* to its outlet *2* (Fig. 2 b). In other words, the angle β_x of the straight bar is less than that of the circular one, as a result of which the tangential force will be lower.

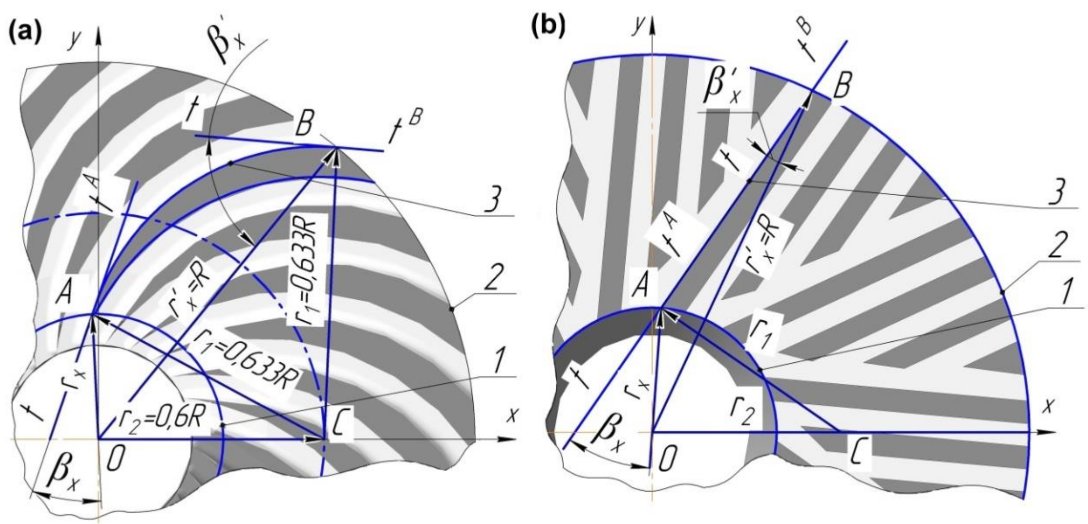


Fig. 1. Geometrical structure of a circular and straight bar (r_1 – curvature radius; r_2 – curvature centre radius; r_x – radius drawn from the curvature centre to the point of tangency; β_x – angle between the tangent t – t^A and the radius r_x drawn from the disc centre O to the point of tangency A; β'_x – angle between the tangent t – t^B and the radius r'_x drawn from the disc centre O to the point of tangency B; cutting edge – 3)

The dependency of the variation of the angle β_x on the current geometrical data shown in Fig. 1 can be expressed in the form of Eq. 1:

$$\beta_x = 90° - \arcsin\frac{r_2 \times \sin\angle C}{\sqrt{r_1^2 + r_2^2 - 2 \times r_1 \times r_2 \times \cos\angle C}} \tag{1}$$

It has been analytically established that the angle β_x increases when the curvature radius r_1 is equal to 0.633R, and the curvature centre radius r_2 is equal to 0.6R (provided that the refiner disc radius is R = 100 mm). Two patents have been obtained for this structural design solution (Alashkevich *et al*. 2021).

Comparative characteristics of the tangential force from the bar angle β_x.

Figure 2 shows a fragment of the front projection of the rotor disc refiner plates with the power components of the circular bar. The circular arrow shows the rotation direction of the rotor disc. The area of the circular refining surface is limited by the circular inlet 1 and outlet 2 edges. The bottom edge of the circular bar 3 intersects with the inlet 1 edge and the Y ordinate at point A. From point A, the vector AE is drawn as an equivalent of the circular force $P^A{}_o$. The force $P^A{}_n$ is projected onto the perpendicular AG to the tangent t - t^A. These lines make up the right-angled force triangle AEG, where the side AG is the normal component $P^A{}_n$ of the circular force $P^A{}_o$. EG is the tangent component $P^A{}_\tau$ of the circular force $P^A{}_o$. From point B, the vector BE' is drawn as an equivalent of the circular force $P^B{}_o$. We project $P^B{}_o$ onto the line BG' perpendicular to the tangent t - t^B. A right-angled force triangle $BE'G'$ is formed, where the side $E'G'$ is the tangential component $P^B{}_\tau$ of the circular force $P^B{}_o$. BG' is the normal component $P^B{}_n$ of the circular force $P^B{}_o$.

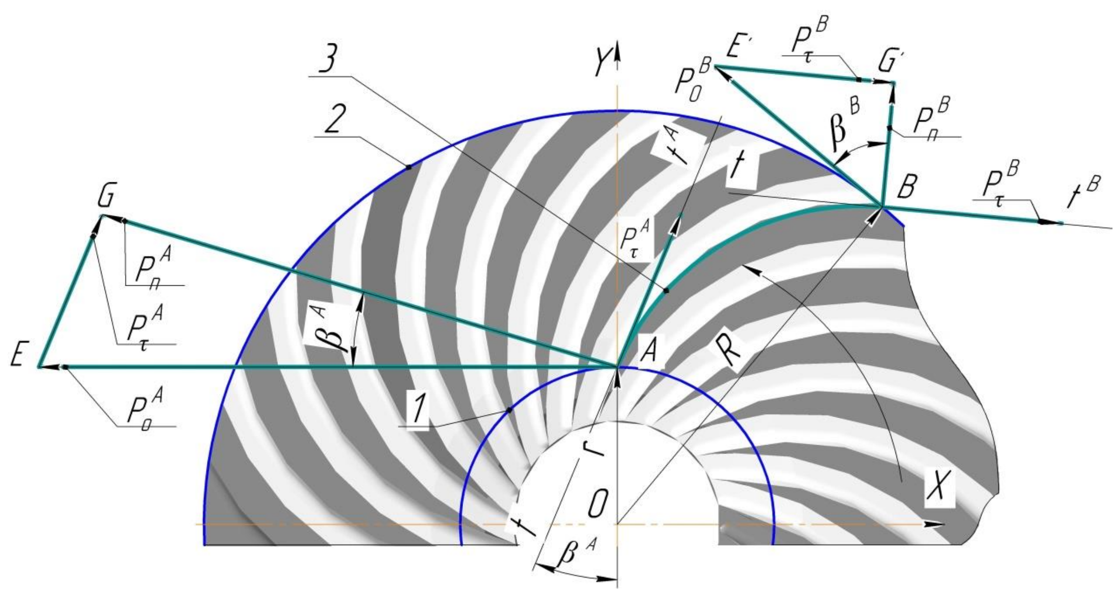


Fig. 2. Fragment of the rotor disc refiner plate with the force components of the circular bar

It is essential to consider a series of properties that influence the functionality of the refiner plate rotor disc. One distinctive characteristic is the fact that from the inlet 1 to the circular refining zone to its outlet 2, the radius r increases from the minimum value at point A to the maximum at point B. The circular force P_o applied at these points (along the tangents t - t^A and t - t^B) to the wall of the circular bar 3 decreases from the maximum $P^A{}_o$ at point A to the minimum $P^B{}_o$ at point B. The torque M around the entire surface of the circular bar 3 is a constant value that can be recorded as Eq. 2,

$$M = P_O^A r \tag{2}$$

where M = 12.7 Nm is the torque required for the ADM100S2 electric motor, (Manufacturer JSC "Uralelectro", city of Mednogorsk, Russia).

Analysis of the ratio of the forces $P^A{}_\tau$ and $P^A{}_o$ from the right-angled triangle AEG can be written as Eq. 3:

$$P_{\tau}^{A} = P_{O}^{A} \times \sin\ \beta^{A} \tag{3}$$

Thus, at any point A_x, the tangent component will be expressed in the form of Eq. 4:

$$P_{O}^{A_x} = \frac{P_{\tau}^{A_x}}{\sin \beta^{A_x}} \tag{4}$$

Replacing $P^{Ax}{}_{o}$ in Eq. 4 with the right-hand side of Eq. 2, we get:

$$\frac{M}{r_x} = \frac{P_{\tau}^{A_x}}{\sin \angle \beta^{A_x}} \tag{5}$$

From Eq. 5, it follows that at point A, the tangential force $P^{A}{}_{\tau}$ will have the form of Eq. 6:

$$P_{\tau}^{A} = \frac{M \times \sin \angle \beta^{A}}{r} \tag{6}$$

The same method was used to obtain the equation for the tangential force at point B:

$$P_{\tau}^{B} = \frac{M \times \sin \angle \beta^{B}}{R} \tag{7}$$

Dividing Eq. 7 by Eq. 6, we obtain a general equation characterising the ratio of the varying tangential forces of the circular bar:

$$\frac{P_{\tau}^{B}}{P_{\tau}^{A}} = \frac{\sin \angle \beta^{B} \times r}{\sin \angle \beta^{A} \times R} \tag{8}$$

Equation 8 determines the force impact in the refining zone due to the tangential component from the beginning of the cutting edge to its end ($P^{A}{}_{\tau}$ and $P^{B}{}_{\tau}$), provided that normal forces and centrifugal forces contribute to the movement of the pulp around the refining area. These forces were not taken into account when solving the given task in this analysis. Taking the tangential components of Eq. 8 into account, we compare the ratio of the tangential forces for refiner plates with circular-shaped bars and for traditional refiner plates with straight bars that were used in this study. Table 1 presents the initial data for the calculation and the types of refiner plate designs.

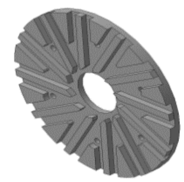
In addition to the bar angle, the pulp freeness quality is also affected by the number of bar crossings expressed in terms of the cutting edge length (CEL) (m/s). The cutting edge length can be found by multiplying the total length of the rotor and stator cutters of the bar plate, as well as by the rotational speed of the disc refiner rotor. According to ISO/TR 11371 (2013), the equation of the cutting edge length is written as Eq. 9:

$$CEL = Z_R \times Z_S \times l \times \frac{n}{60}, \text{ [m/s]} \tag{9}$$

where Z_R and Z_s are the numbers of the plate rotor and stator cutters; l is the total length of cutters (m); and n is the rotor speed.

In this article, the cutting edge length for each plate in the study was calculated. Table 1 presents information on the bar and groove widths.

Table 1. Comparative Characteristics of Various Plate Designs

	With Circular Bars	Sectoral With Straight Bars	With Straight and Evenly Distributed Bars
Type of Refiner Plate			
r (mm)	38	38	38
R (mm)	100	100	100
β^{A} (°)	22.6	22.6	22.6
β^{B} (°)	54.1	8.2	11.4
P^{B}_{T} (N)	102.8	18.1	25.1
Bar widths (mm)	7	6	8
Groove widths (mm)	6,5	6	10
CEL (m/s)	1,709	3,379	1,114

It is clear from Table 1 that the tangential force of the refiner plate design with circular bars is higher than that of traditional refiner plates with straight bars. This is because the angle β_x formed between the tangent to the active wall of the cutting edge and the radius drawn from the centre of the disc to the tangency point of the straight bars decreases from the centre to the periphery (Kovalev 2007). The quantitative values of the cutting edge length and the width of the bars and grooves in the studied bar plates differ from each other. Let us consider the change in the external fibre fibrillation and its influence on the strength characteristics of handsheets during high-consistency pulp refining taking into account the parameters presented in Table 1.

Refining

LS 1-grade bleached hardwood sulphate pulp manufactured by Ilim Group from Bratsk (Russia) was used for the experiment. This pulp was selected because high-consistency pulp refining allows preserving the initial fibre length to a greater extent, which is essential when refining pulp of such short-fibre wood species as hardwood. Moreover, paper sheets produced from hardwood will have qualities that are hard or impossible to achieve using long-fibre softwood pulp. These qualities include an even design and a smooth surface of the sheet, softness, bulkiness, high transparency, low deformability of different types, and better writing and typing qualities.

The refining was completed on a laboratory disc refiner presented in Fig. 3. The working principle of the disc refiner is as follows: the pulp of the required consistency is placed in tank 9, where, under its own weight, it enters the zone of screw feeder 5, which transports it to the disc refiner refining zone 1, where it is refined between the rotor 2 and the stator 3. The pulp is then passed through the outlet 10. Screw feeder 5 is rotated by the electric motor 7 *via* the worm gear 8. The disc refiner rotor is rotated by the electric motor 6.

Prior to refining, the pulp was disintegrated in accordance with ISO 5263-3 (2004). The refining was performed at a pulp consistency of 10%, 15%, and 20%. The rotor speed was 2,000 rpm, and the gap between the rotor and the stator was 1.5 mm. This gap was chosen primarily because the proportion of fines increased in the fractional composition of the pulp, and fibre cutting was observed with gaps of less than 1.5 mm. When conducting experimental studies, the pulp was required to repeatedly pass through the refining zone to achieve the required pulp freeness value. When using the plates with circular bars, the pulp was required to pass 11 times through the refining zone to achieve a freeness value of 60°SR. 16 times were required for the sectoral refiner plates with straight bars, while 14 times were required for the refiner plates with straight bars and their uniform distribution.

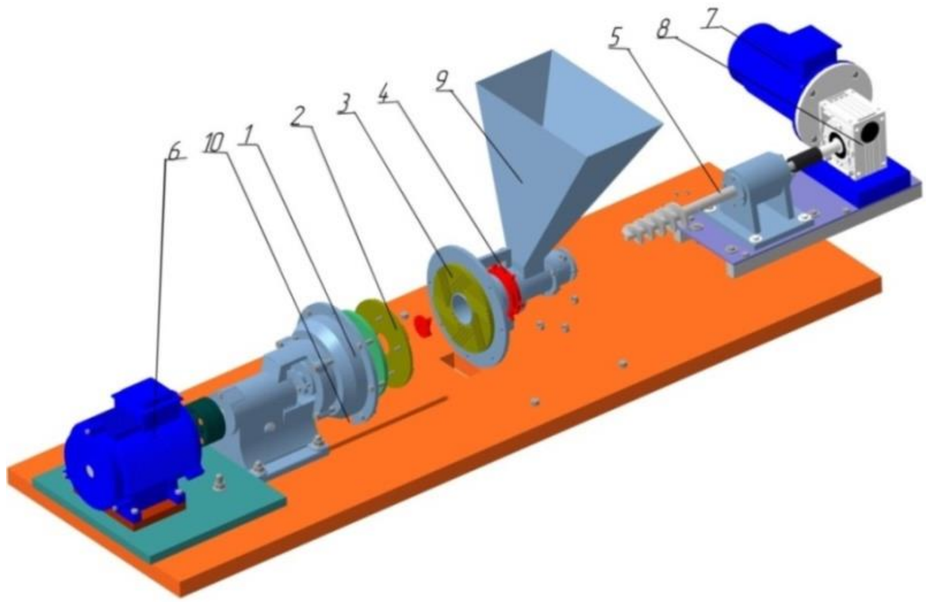


Fig. 3. Design of disc refiner (1 – refining zone; 2 – rotor; 3 – stator; 4 – adjusting device; 5 – screw feeder; 6 – rotor electric motor; 7 – screw feeder drive electric motor; 8 – worm gear; 9 – hopper; 10 – output)

Specific refining energy consumption was evaluated using a C6803V M7 R31 electric metre by Energomer (Stavropol, Russia). Upon reaching the required freeness value, the specific energy consumption was recorded depending on the quantity of the pulp that passed through the refining zone (kWh/t).

Test methods

To study the external fibre fibrillation degree depending on the number of passes of the pulp through the disc refiner's refining zone, the increase in the pulp freeness value was determined using the Schopper-Riegler method in accordance with ISO 5267-1 (2000). The samples were taken at freeness values of 15 to 60 °SR with an interval of 15 °SR. The fibrillation index characterising the external fibrillation of the fibre was determined at least three times for each sample using the *Morfi neo* fibre analyser (Manufacturer "TECHPAP", Gieres, France) in accordance with ISO 16065-2 (2019). The device is adjusted for measuring at least 5,000 fibres in each studied sample.

The effect of external fibrillation on the handsheets was evaluated in terms of the breaking length, bursting strength, and tear resistance in accordance with ISO 1924-1 (1992), ISO 2758 (2014), and ISO 1974 (2012), respectively. For these purposes, handsheets of pulp of various freeness values (15, 30, 45, and 60 °SR) were made on a sheet former (Werkstoffprufmaschinen, Leipzig, Germany).

Before testing the strength characteristics, handsheets that had been tested in terms of their physical and mechanical characteristics were conditioned under standard atmospheric conditions ISO 187 (2022) (relative humidity ± 2%, ambient temperature 23 ± 3 °C). The breaking length of the handsheets was tested on an RMB 30M (Experimental Production Workshop, Moscow, Russia) breaking machine. The bursting strength of the handsheets was tested on an EC35 (TMI 13-6, Amsterdam, Netherlands) bursting strength machine. The tear resistance of the handsheets was tested on an RB-1 (Experimental Production Workshop, Moscow, Russia) device.

Although the phenomena associated with internal and external fibrillation have not been quantitatively evaluated and compared, they are closely interrelated. Without excluding the role of internal fibrillation, external fibrillation is just its consequence, as the fibres develop during refining. External fibrillation results in partial fibril detachment. The fibrils then remain attached to the fibres, thereby affecting their uniformity (Page 1989). Taking into account the design features of bar plates, high-consistency pulp refining results in intensive fibre grinding, which should affect external fibrillation. This study quantitatively evaluated external fibrillation in terms of the fibrillation index.

The fibrillation index *"Fib"* is determined by the fibre analyser as the ratio of the sum of all fibril lengths to the sum of all recognised fibre lengths, expressed as Eq. 10,

$$Fib = \frac{\sum_{i=1}^{N} F_i}{\sum_{i=1}^{N} L_i} \times 100\% \qquad (10)$$

where F_i is the overall length of all individual fibrils on the fibre f_X (f_A, f_B, f_C…), as shown in the design model in Fig. 4 (a) and L_i is the fibre length (mm).

To visually evaluate external fibrillation and compare the data obtained from a fibre analyser, the fibres were additionally subjected to scanning electron microscopy on a Hitachi SU3500 microscope by Hitachi High-Technologies Corporations (Tokyo, Japan). Fig. 4 (b) shows the external fibrils identified in the microscope pictures.

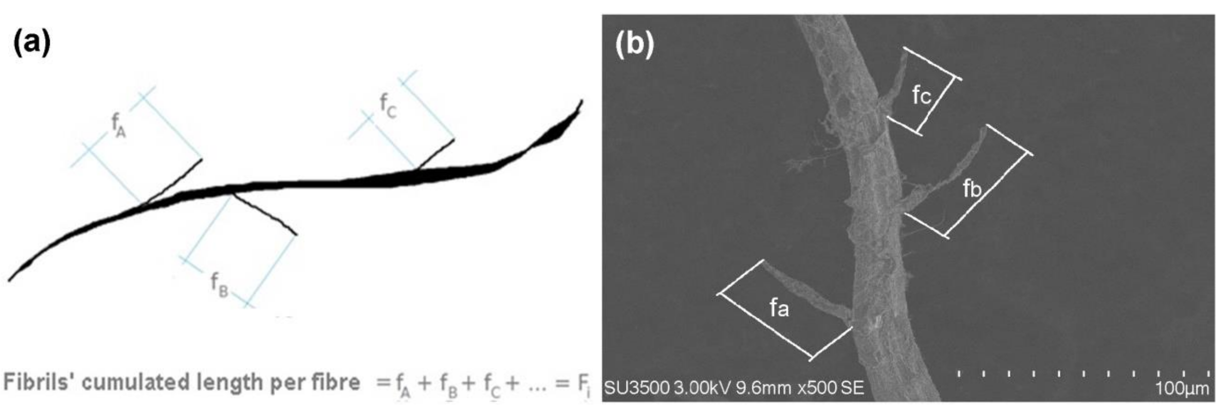


Fig. 4. Identification of the external fibrils: (a) – using the fibre analyser; (b) – using scanning electron microscopy

RESULTS AND DISCUSSION

Fibrillation Index Variation

Figure 5 presents histograms of the fibrillation index distribution depending on the freeness values of pulps of various consistency obtained using various refiner plate designs.

The fibrillation index of the initial fibres at a freeness value of 15°SR was 0.846%. With an increase in the freeness value to 60 °SR, this parameter increased by 2.4 times (at a pulp consistency of 10%) for the plates with circular bars and on average by 1.6 times for traditional bars. This phenomenon is explained by the high tangential force of the plate with circular bars, which leads to an increase in interfibre friction, resulting in external fibre fibrillation. Analysing the data obtained, it is clear that the cutting edge length (CEL), which determines the intensity of influence on the fibres, does not directly depend on the fibrillation index. Thus, sectoral plates with straight bars have a CEL index that is 2 times higher than those with circular bars (Table 1) but provide significantly lower quantitative values of the fibrillation index.

The fibrillation indices presented in this paper visually demonstrate its tendency of decreasing as the pulp consistency increases. This phenomenon is explained by the fact that at different stages of high-consistency pulp refining, the cellulose fibre may undergo such deformation as axial twist, which decreases its fibrillation capacity (Klark 1983). High fibrillation index values were reached using pulp of 10% consistency and refiner plates with circular-shaped bars.

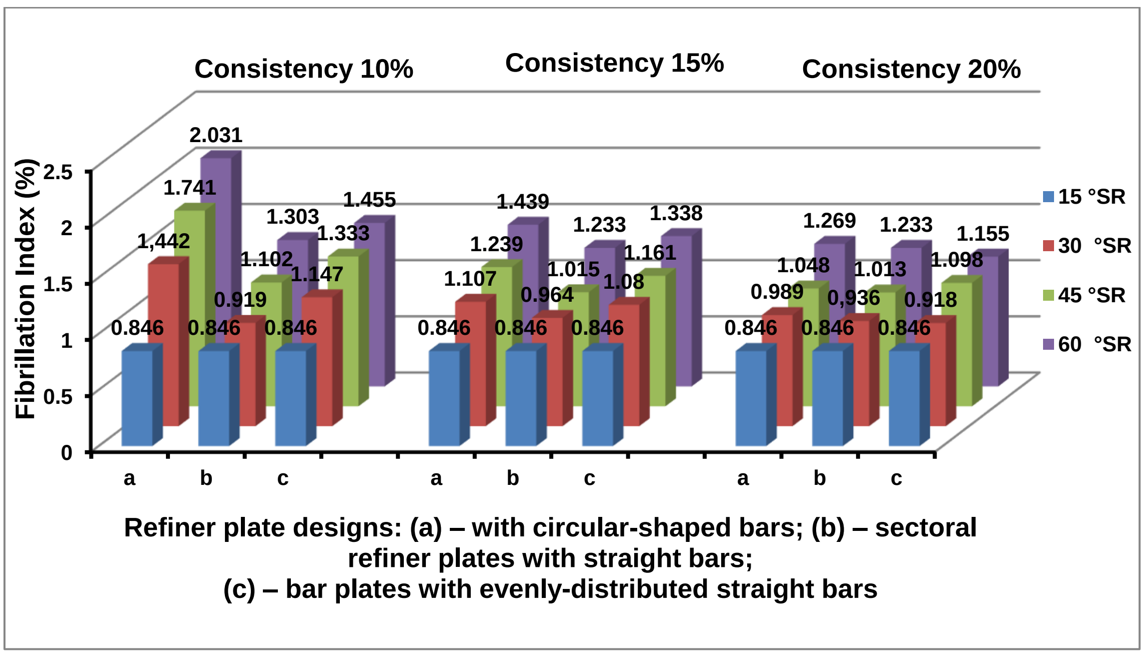


Fig. 5. Dependence of the fibrillation index on the freeness value for pulps of various consistency using different refiner plate designs

For a visual evaluation of the external fibrillation of the fibre, some samples were taken after refining the pulp of 10% consistency and 60 °SR freeness. Images showing the fibres after the refining are presented in Figs. 6 to 8. As shown in Fig. 6, the external fibrillation degree was noticeably different in fibres refined using circular-shaped refiner plates. A circular bar ensures distinctive stripping of the fibrils, while the fibrils remain attached to the fibre surface.

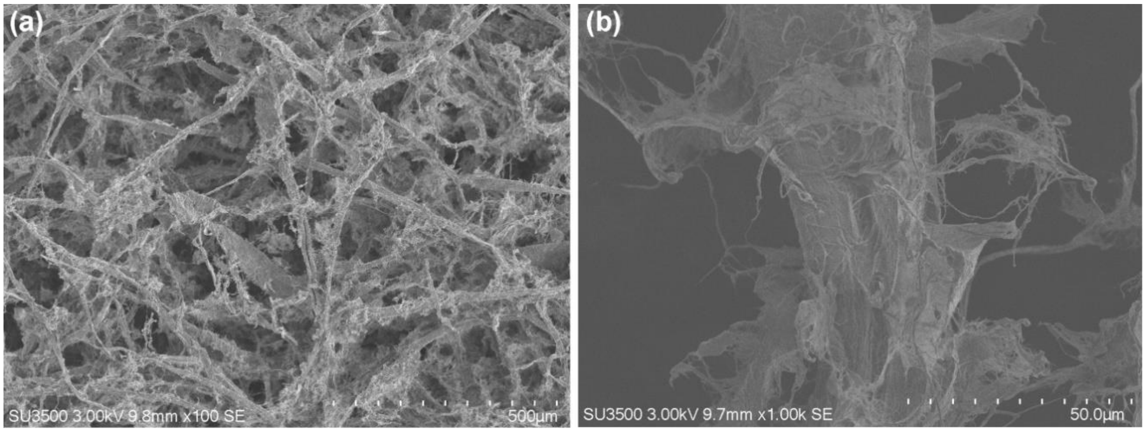


Fig. 6. SEM images of the morphological structure of fibres refined using refiner plates with circular bars; (a) – fibre overview; (b) – single fibre view

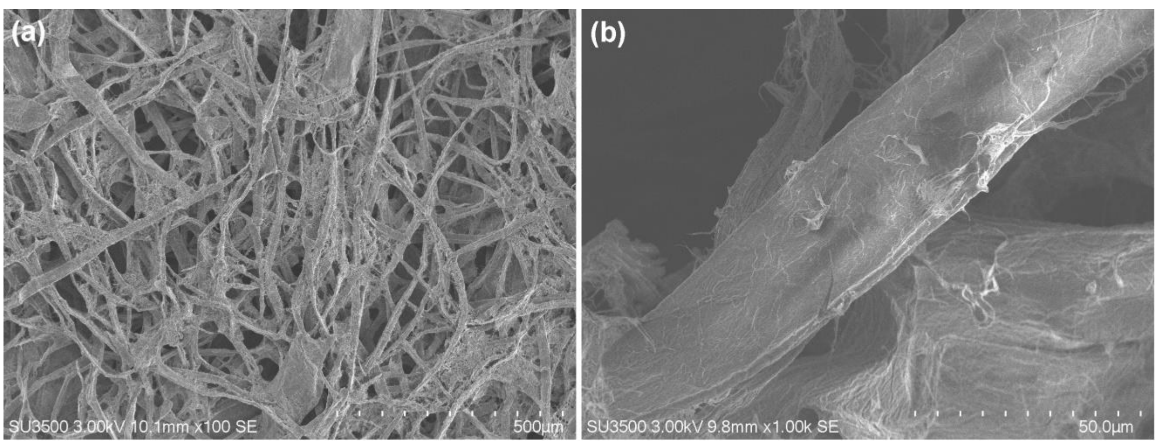


Fig. 7. SEM images of the morphological structure of fibres refined using sectoral refiner plates with straight bars; (a) – fibre overview; (b) – single fibre view

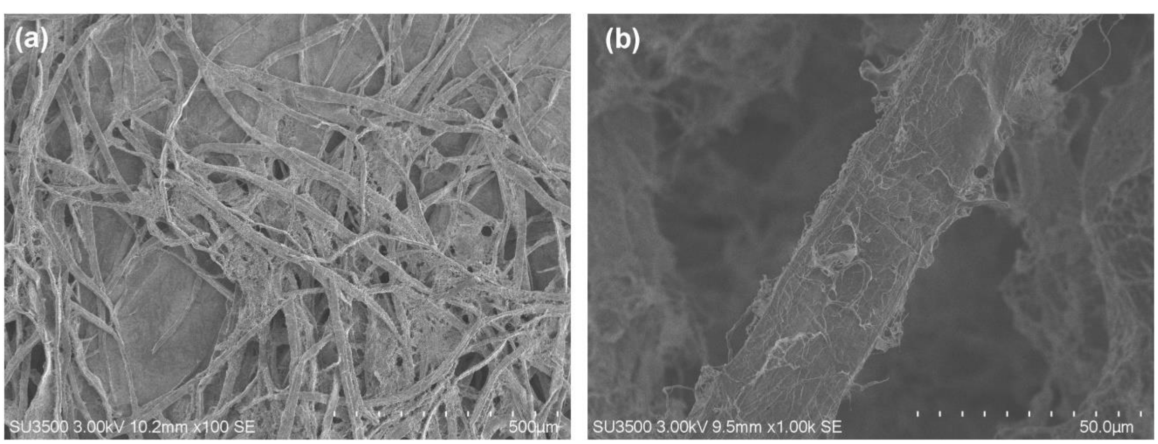


Fig. 8. SEM images of the morphological structure of fibres refined using refiner plates with evenly-distributed straight bars; (a) – fibre overview; (b) – single fibre view

External fibrillation of fibres refined using traditional straight refiner plates was less prominent. This is evidenced by the minor fibrous fluff that appeared as a result of the stripping of the primary and secondary walls of the fibre (Figs. 7, 8). The presence of fibrils stripped from the fibres as a result of external fibrillation, apparently, should impact the strength characteristics of the handsheets. To verify this assumption, studies were conducted on the general physical and mechanical properties of handsheets depending on the fibrillation index using different refiner plate designs.

Variation of the physical and mechanical properties of handsheets depending on the fibrillation index when using different refiner plate designs

Figures 9 to 11 present the dependence of the variation of the breaking length, bursting strength, and tear resistance on the fibrillation index at different pulp consistencies when using different refiner plate designs. In all cases, the quantitative values of the breaking length (Fig. 9), bursting strength, and tear resistance (Figs. 10 and 11) when using refiner plates with circular bars were higher compared to those achieved using refiner plates patterns with straight bars.

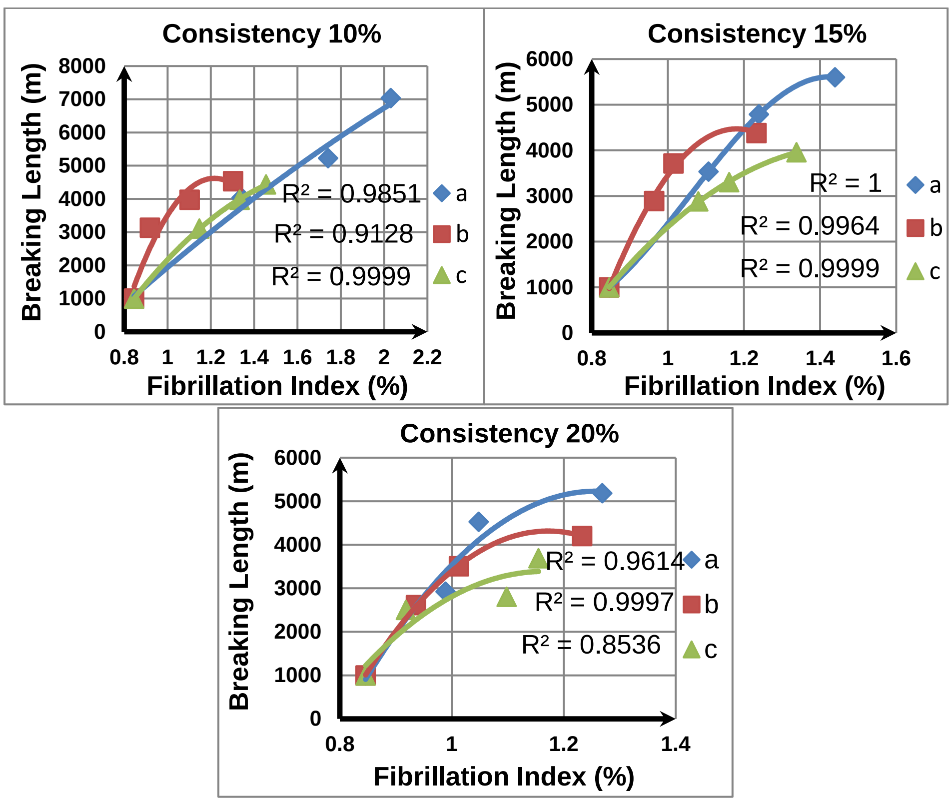


Fig. 9. Dependence of breaking length on the fibrillation index for different pulp consistencies and different refiner plate designs: (a) – with circular bars; (b) – sectoral with straight bars; (c) – with evenly distributed straight bars

In addition to the above finding, the physical and mechanical dependencies depended on the pulp consistency. The breaking length when using refiner plates with circular bars and 10%-consistency pulp was 7,000 m.

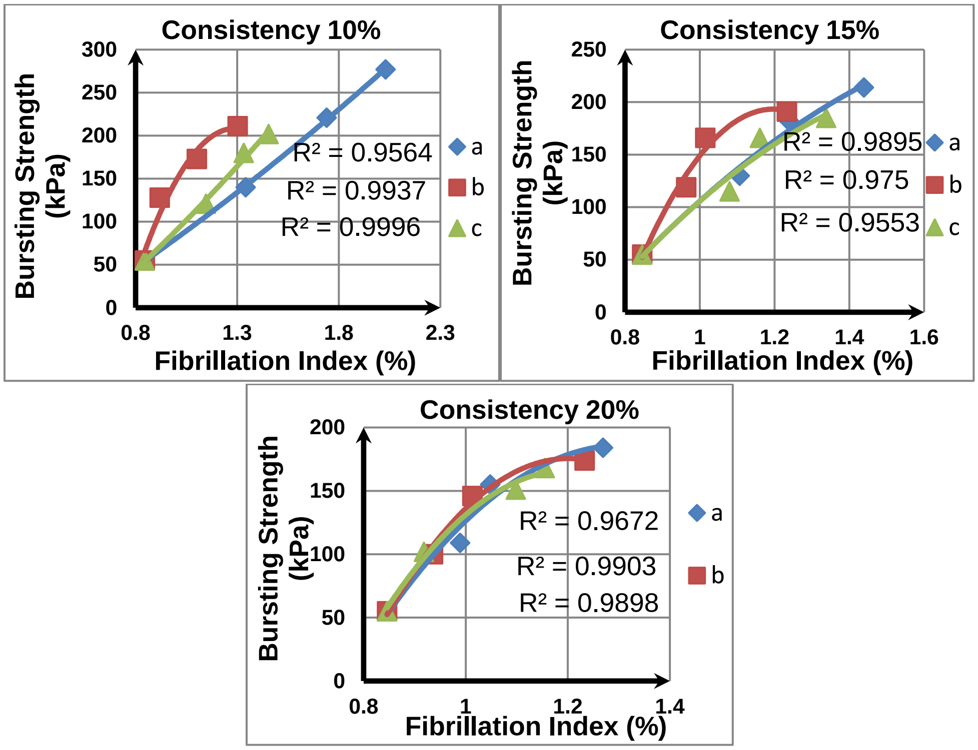


Fig. 10. Dependence of bursting strength on the fibrillation index for different pulp consistencies and different refiner plate designs: (a) – with circular bars; (b) – sectoral with straight bars; (c) – with evenly distributed straight bars

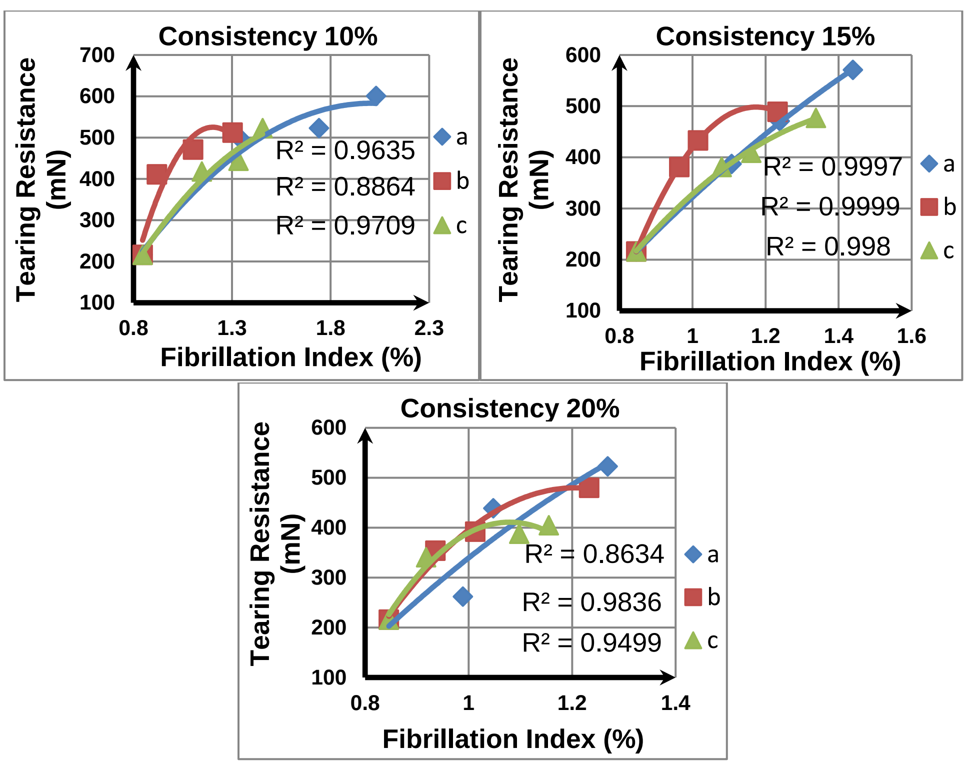


Fig. 11. Dependence of tear resistance on the fibrillation index for different pulp consistencies and different refiner plate designs: (a) – with circular bars; (b) – sectoral with straight bars; (c) – with evenly distributed straight bars

For 15% pulp consistency, the breaking length values varied around 5,500 m. A further increase in the pulp consistency to 20% led to a decrease in the breaking length to 5,200 m. A similar pattern was observed in the variation of the bursting strength and tear resistance values.

It is worth noticing that in all cases, a difference in the qualitative dependencies of the curves was observed. At a pulp consistency of 10% and using refiner plates with circular bars, the dependencies of the breaking length and bursting strength values on the fibrillation index were linear. The same dependence is observed for the tear resistance value at pulp consistencies of 15% and 20%. The qualitative dependences of the physical and mechanical properties are parabolic when using traditional refiner plates with straight bars.

The reduction in the physical and mechanical properties of the handsheets as a result of the increase in pulp consistency may occur due to such cellulose fibre deformation as axial twist, which decreases its fibrillation capacity (Reiska *et al.* 1972; Klark 1983). This phenomenon can also be explained by the fact that with an increase in the pulp consistency during refining, the refining zone temperature increases due to intense interfibre friction, and as a consequence, the pulp hemicelluloses may destruct, which entails a decrease in the strength of handsheets (Pen and Karetnikova 2008).

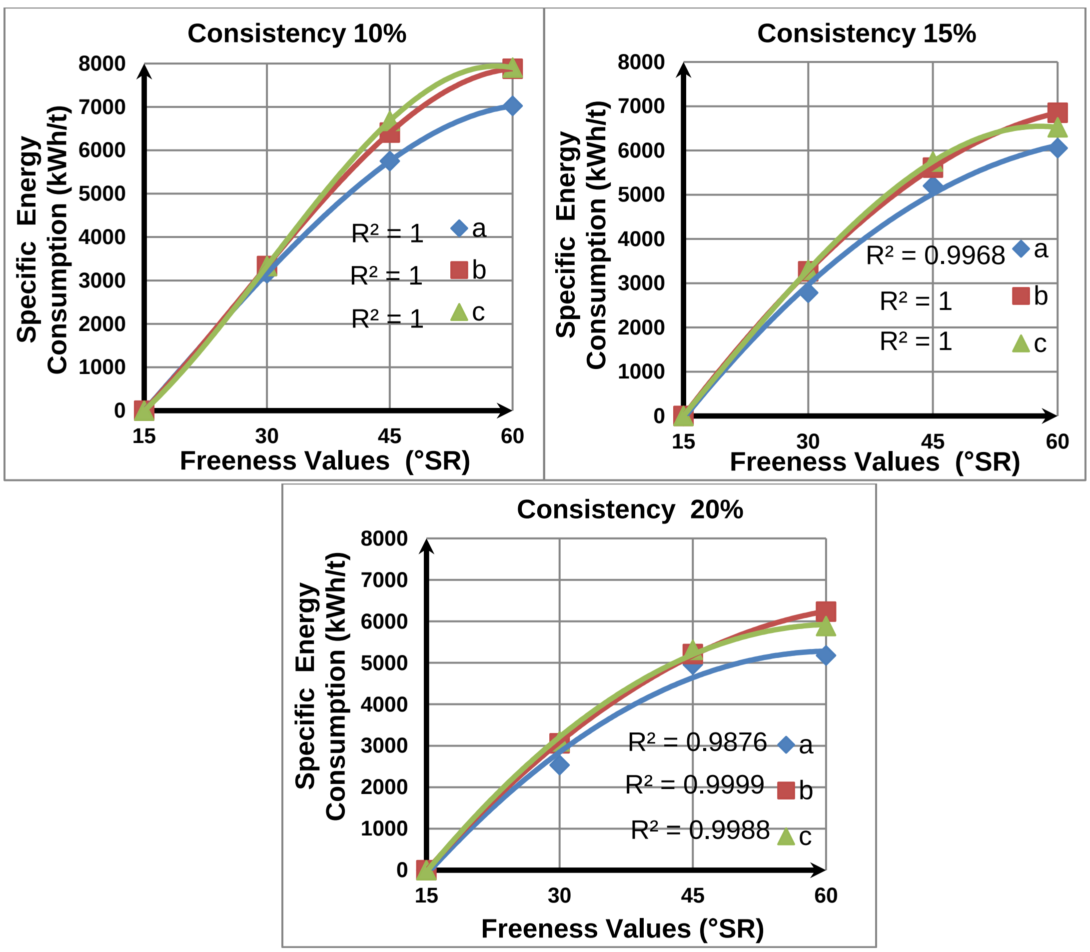


Fig. 12. Dependence of specific energy consumption on the freeness values for different pulp consistencies and different refiner plate designs: (a) – with circular bars; (b) – sectoral with straight bars; (c) – with evenly distributed straight bars

Figure 12 shows the specific refining energy consumption at various pulp consistencies. An increase in the pulp consistency led to a decrease in the specific refining energy consumption. To achieve a freeness value of 60°SR when refining pulp with a 20% consistency, the specific energy consumption was on average 6,000 kWh/t, which was 25% less than for 10% consistency.

The specific energy consumption for refining using plates with circular bars at equal freeness values (60°SR) and a pulp consistency of 20% was 7,000 kWh/t, which was 13% less than that of traditional plates with straight bars. Almost the same situation was observed for a pulp consistency of 15% and 20%. When compared to traditional plates with straight bars, the use of circular bars decreases the specific refining energy consumption due to the peculiarities of the cutting edges and their force impact on the fibres. The tangential force of the circular bar P^{B}_{τ} was on average 2.5 times higher, which ensures more intensive pulp processing in the refining zone.

CONCLUSIONS

1. High-consistency pulp refining was discovered to cause pronounced external fibrillation of fibres, as evidenced by the fibrillation index data. There was a close relationship between the fibrillation index and the physical and mechanical characteristics. A 50% increase in the fibrillation index (at a freeness value of 60°SR) resulted in an up to 40% increase in the physical and mechanical characteristics (breaking length, bursting strength and tearing resistance).

2. The fibrillating effect on the fibre during high-consistency pulp refining can be caused not only by the inter-fibre frictional forces, but also the tangential forces occurring on the refiner plate bars. Based on the fibrillation index data, the highest external fibrillation was observed in the pulp that was refined using refiner plates with circular bars in which the tangential force has a higher quantitative value than that of the traditional refiner plates with straight bars. The highest external fibrillation was found in the pulp refined at a 10% consistency. The resulting external fibrillation does not exclude the need for fibre uniformity during refining and can affect it. This is because the external fibrils formed on the fibre surfaces act as a connecting link in paper web formation, thereby affecting its strength characteristics.

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