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Impact of shredding degree on papermaking potential of recycled waste

Aneta Lipkiewicz[1], Edyta Małachowska[1,2]✉, Marcin Dubowik[1] & Piotr Przybysz[1,2]

The properties of paper products depend on the structure of the cellulose fibres therein. Although fibre properties in virgin pulps can be modified by a refining process, this is more difficult in pulp from recovered fibre, particularly waste from office shredders that tend to shorten fibres during shredding. The shorter fibres in shredded paper make it difficult to easily reconstitute them into high-quality paper products. Moreover, because of high energy usage during the recycling process and transportation inefficiencies, there is a need to determine how to responsibly shred paper to alleviate this environmental burden. With this in mind, the influence of initial fibre length on the tensile properties of paper was investigated. Changes in initial fibre length significantly influenced many pulp and paper properties. It was found that cutting the paper into pieces with an area less than 25 mm² caused significant changes in the important morphological parameters of the fibres and a sharp decrease in the tensile properties of the reconstituted paper.

Wastepaper, for both ecological and economic reasons, is a good raw material for the production of paper or cardboard. Paper recycling reduces the use of wood, and thus, helps preserve forest resources, saves energy, reduces littering, the amount of waste going to landfills, air pollution, and wastewater generation, and instils ecological attitudes in society.

However, the properties of fibres in wastepaper can deteriorate not only during processing, but also at the collection stage due to shredding, which can cause excessive shortening of the fibres. In addition to fibre bonding[1], fibre length and strength are basic factors influencing the tensile and structural properties of paper products[2–4]. Fibre and pulp properties also affect the cost of producing paper products. Hence, the ability to control fibre properties during the recycling stage is a determining factor in effective quality control and the cost of paper production from waste paper.

In industrial practice, the fibres are shortened as a direct result of the fibre refining process or by high-shear processing of the fibrous suspension in the refining zone[5,6]. Therefore, the process of pulp refining has a direct influence on fibre properties, and consequently the properties of the final product[7–9]. Through refining, the properties of the refined pulp can be modified to obtain paper with the desired properties. The refining process, aside from affecting paper properties, also has a decisive impact on the unit energy consumption in this process[10–13]. Owing to the increasing global growth of the market for paper products[14,15], it is extremely important to minimise the unit energy consumption in this process and optimise the development of useful properties of the paper during processing.

Changes taking place in the structure of the refined fibres during the refining process determine how the pulp behaves during web formation and the basic properties of the paper that is produced[16,17]. Fibre shortening has a direct negative impact on the dynamic properties of paper, including its tear resistance[18,19]. Often, refining is consciously carried out to improve the conditions of web forming and improve its transparency.

When paper is thrown into shredders, the objective is to destroy documents; however, the process also unconsciously shortens the fibres. Paper shredders should facilitate the preparation of pulped materials for further production, rather than render the paper useless. Cut fibres in the shredded paper make it difficult to carry out easy reconstitution into high-quality paper products. Moreover, most recycling centres do not handle small strips or bits of paper. Large-scale recycling facilities use large screens to dry pulped paper on, and finely shredded paper is not well retained and can fall through the screens. Reports claim that the utilisation or recycling of shredded paper is much more problematic than that of mixed unshredded paper. The Environmental Paper Network, a worldwide association of 140 civil society groups and NGOs concerned with the sustainability of pulp and paper

[1]Natural Fibers Advanced Technologies, 42A Blekitna Str., 93-322 Lodz, Poland. [2]Institute of Wood Sciences and Furniture, Warsaw University of Life Sciences - SGGW, 159 Nowoursynowska Str., 02-787 Warsaw, Poland. ✉email: edyta_malachowska@sggw.edu.pl

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Specific security levels	Paper media requirements
P-1	12 mm strips or maximum particle surface area of 2.000 mm^2
P-2	6 mm strips or maximum particle surface area of 800 mm^2
P-3	2 mm strips or maximum particle surface area of 320 mm^2
P-4	Maximum cross cut particle surface area 160 mm^2 with a maximum strip width of 6 mm = 6 × 25 mm
P-5	Maximum cross cut particle surface area 30 mm^2 with a maximum strip width of 2 mm = 2 × 15 mm
P-6	Maximum cross cut particle surface area 10 mm^2 with a maximum strip width of 1 mm = 1 × 10 mm
P-7	Maximum cross cut particle surface area 5 mm^2 with a maximum strip width of 1 mm = 1 × 5 mm

Table 1. Requirements for machines and processes shredding documents (DIN 66399).

practices suggests shredding paper only when necessary[20], especially since destruction also increases the bulk density of the paper, reducing its transportation efficiency. The office waste problem is particularly significant because of the high amount generated. For example, Japan has a paper collection rate of around 81.6%[21], which is higher than that of other countries. However, this high collection rate is mainly constituted by a high recycling rate for paper grades such as cardboard and newspapers. The collection rate for office paper and shredded paper remains low (less than 60%)[21] because office paper, on which confidential information is often printed, is generally disposed of. In U.S. offices, 50% of business waste is composed of paper. Offices use approximately 12.1 trillion sheets of paper per year, and paper accounts for 25% of landfill waste and 33% of municipal waste. It was found that each tonne of recycled paper allows for 64% energy savings, 58% water savings, and 60 pounds less air pollution[22]. Security issues aside, one should consider how to efficiently destroy documents while still allowing fibres to be efficiently used in further processing, which will enable the above savings; this paper attempts to address this issue.

Paper destruction categories are assigned based on the standard German Deutsches Institut für Normung (DIN) classification for paper shredding machines. DIN 66,399 classifications, in which 'P' refers to 'Paper-Based' material, are based on the size and type of particle (Table 1).

The aim of this study is to examine the effect of the surface area of shredded particles on paper properties. The study therefore estimates the extent to which waste paper can be shredded while still producing a high-quality product. Pulp samples with different initial particle sizes treated under constant papermaking conditions were used for this purpose.

Materials and methods

Sample preparation. Industrial air-dried and bleached kraft pine pulp in the form of sheets (Arctic Paper Kostrzyn S. A.) was used in this study. In order to keep all other parameters constant, samples of the pulp were cut manually into squares of different areas (1–400 mm^2) to reduce and diversify the fibre length.

Hand-cut samples were compared with strips from shredding machines (destroyed in accordance with DIN 66399). The following shredders were used for the tests: Kobra 240.1 S2 ES (for strips with P-3 specific security levels), HSM Shredstar S5 (for strips with P-4 specific security levels), HSM Securio C18 (for strips with P-5 specific security levels), and HSM Securio B26 (for strips with P-6 and P-7 specific security levels). All cutting processes in the shredders were performed without the addition of oil.

Production of paper sheets and analysis of pulp and paper properties. Sheets of paper from the cut samples were produced under laboratory conditions from rewetted pulp samples (22.5 g dry weight samples were soaked in water for 24 h) that were subjected to disintegration using a laboratory JAC SHPD28D propeller pulp disintegrator (Danex, Katowice, Poland) for 23.000 revolutions, according to ISO 5263-1 (2004). The disintegrated pulps were concentrated to a dry weight content of 10% and refined in a JAC PFID12X PFI mill (Danex, Katowice, Poland) under standard conditions [ISO 5264-2 (2011)]. All the samples were refined for a constant time of 120 s. After the model pulp recycling processes, including refining, the following properties of the pulps were evaluated:

- Schopper-Riegler freeness parameter (SR) was measured using a Schopper–Riegler apparatus (Danex, Katowice, Poland) in accordance with PN-EN ISO 5267-1 (2002);
- The water retention value (WRV) was determined according to ISO 23714 (2014);
- The dimensions of the fibre parameters were measured according to ISO 16065-2 (2016) using a Morfi Compact Black Edition apparatus (Techpap, Grenoble, France).

In the next step, sheets of paper were formed in a Rapid-Koethen apparatus in accordance with PN-EN ISO 5269-2 (2007). Each paper sheet had a basis weight of 80 g/m^2 (according to ISO 536:2012). Only sheets with basis weights between 79 and 81 g/m^2 were used for further investigation. The sheets were conditioned for 24 h at a relative humidity of 50 ± 2% and a temperature of 23 ± 1°C [ISO 187 (1990)] before determining their properties. The properties of the paper sheets were examined as follows. A ZwickRoell Z005 TN ProLine tensile testing machine (Zwick-Roell, Ulm, Germany) was used to measure the mechanical properties of the paper in accordance with PN-EN ISO 1924-2 (2010). The roughness and air permeability were measured using a Bendtsen apparatus (Messmer Buchel, Veenendaal, The Netherlands).

Sample dimensions (mm)	Sample area (mm²)	Freeness (°SR)	WRV (%)
1 × 1	1	51	214.5 (3.4)
2 × 2	4	42	212.5 (2.2)
1 × 5 (P-7)	5	39	211.1 (1.2)
3 × 3	9	31	208.5 (1.6)
1 × 10 (P-6)	10	31	208.1 (1.3)
4 × 4	16	30	207.2 (1.4)
5 × 5	25	29	206.8 (1.2)
2 × 15 (P-5)	30	28	206.3 (1.5)
6 × 6	36	28	206.1 (1.9)
8 × 8	64	26	205.2 (2.5)
10 × 10	100	25	205.6 (1.8)
6 × 25 (P-4)	150	25	204.8 (2.2)
P-3	320	25	203.6 (2.8)
20 × 20	400	25	202.8 (1.6)
Reference	–	25	201.2 (3.1)

Table 2. Characteristics of refined cellulose pulps. Standard deviation are given in brackets.

The average degree of polymerisation (DP) of cellulose in each pulp was determined using the viscometric method described in ISO 5351 (2010).

Results and discussion

In industrial conditions, the freeness index of pulp is a commonly used parameter to assess the degree of refining of pulp based on how easily it dewaters. The dewatering of pulp on a paper machine screen is a very useful indicator in industrial practice; therefore, in this study, the effect of the initial fibre length on changes in this indicator was examined. Table 2 shows that the freeness of the refined pulp decreases as the initial fibre length increases, which is attributed to the decreasing amount of fine material in the pulp, in line with the current state of knowledge[23–28]. It is assumed that a freeness index of about 30°SR is optimal for most papermaking properties[29,30]. However, obtained results do not indicate that a freeness of ~ 30°SR necessarily achieves a maximum tensile strength (Table 2). This confirms that there is no straightforward relationship between freeness and paper properties. Therefore, the freeness of the pulp is not useful to compare the papermaking potential of pulp with different initial parameters.

The impact of initial fibre length on internal fibrillation, one of the basic effects of refining[31–35], was also studied. Progress in achieving internal fibrillation of refined fibres is commonly assessed based on an increase in their swelling[36,37], usually measured by the WRV[38–40]. The analysis in Table 2 indicates that the WRV increases as the initial fibre length decreases, reaching a maximum value of 214.5%. This increase in fibre swelling is accompanied by an increase in the density of the paper, which in turn increases the resistance of the paper to air permeability (Table 2), consistent with previous studies[8,41–43].

The initial fibre length did not affect the DP of the produced pulps. The DP was 931 ± 0.89 regardless of the initial dimensions of the samples tested. This confirms previous findings in the literature that mechanical treatment has little effect on the DP of cellulose[44,45].

Table 3 and Fig. 1 show the morphological characteristics of the fibres of the examined pulps. The fibre length for the refined pulps is characterised by lower values compared to the unrefined pulps, which confirms that one of the basic effects of refining is fibre shortening[46–48]. It should be noted that the use of mean weighted or mean geometric fibre length eliminates the influence of the fines fraction on the analysis result[49,50].

The results presented in the Table 3 show that the examined parameter values of fibres and pulps (mean fibre width, mean fibre coarseness, macro fibrillation index, broken fibre content, and fine content) tend to decrease with decreasing length of the initial fibres, and consequently, the mean weighted fibre length increases. However, an initial sample length greater than 5 mm does not significantly affect the examined fibre properties and fine content. It is therefore likely that a strip width of 5 mm is the limit above which significant changes in the pulp do not occur. The results are similar before and after the refining process (Fig. 1).

Microscopic images of the refined pulps, recorded using a Morfi Compact Black Edition camera, are shown in Fig. 2. The decrease in fibre length after the model pulp recycling process is proportional to the decrease in the dimensions of the pre-cut pulp samples. The most significant fibre shortening is noticed for the 1 × 1 mm sample. There is no significant difference in fibre dimensions for the 10 × 10 mm samples and the reference sample (Fig. 2). Therefore, it is possible to shred paper in a shredder to a specific level of fragmentation without fear of excessive shortening of the fibres, which would make the production of high-quality paper more difficult.

According to previous findings, fibre length has a significant impact on the paper stretch index[51], and excessive fibre shortening and a high fines content cause the paper product to become rigid and reduce its deformability[49,52,53]. Our results, however, indicate that the stretch of the examined papers is similar, irrespective of the fibre length and fines fraction content (Table 4), in contrast to previously reported results. However,

Sample area	Mean fibre width	Mean fibre coarseness	Macro fibrillation index	Broken fibre content	Fine content
mm²	μm	mg/m	%	%	% in area
1	32.9 (0.1)	0.207 (0.017)	1.135 (0.047)	52.3 (1.1)	11.70 (0.54)
4	32.4 (0.3)	0.199 (0.009)	1.085 (0.007)	50.0 (0.5)	9.42 (0.13)
5	32.5 (0.2)	0.197 (0.008)	1.059 (0.009)	49.3 (0.6)	9.20 (0.19)
9	31.9 (0.1)	0.190 (0.011)	0.890 (0.023)	45.8 (0.4)	6.85 (0.24)
10	31.8 (0.2)	0.195 (0.007)	0.903 (0.020)	46.1 (0.3)	6.78 (0.18)
16	31.5 (0.1)	0.196 (0.006)	0.861 (0.011)	44.9 (0.8)	5.98 (0.18)
25	31.7 (0.4)	0.195 (0.001)	0.832 (0.007)	43.8 (1.5)	5.51 (0.14)
30	31.5 (0.3)	0.193 (0.002)	0.819 (0.006)	43.6 (1.1)	5.26 (0.16)
36	31.2 (0.2)	0.191 (0.008)	0.814 (0.005)	43.0 (0.6)	5.08 (0.28)
64	31.5 (0.1)	0.187 (0.009)	0.799 (0.012)	41.5 (0.2)	4.26 (0.14)
100	31.1 (0.1)	0.182 (0.012)	0.764 (0.022)	39.3 (0.6)	3.25 (0.21)
150	31.0 (0.3)	0.184 (0.011)	0.769 (0.015)	39.8 (0.4)	3.04 (0.18)
320	30.8 (0.1)	0.183 (0.010)	0.752 (0.012)	38.4 (0.4)	2.95 (0.10)
400	30.9 (0.4)	0.184 (0.001)	0.758 (0.058)	39.2 (0.5)	3.00 (0.60)
Reference	30.7 (0.3)	0.180 (0.010)	0.777 (0.024)	35.4 (0.6)	2.81 (0.60)

Table 3. Fibre and pulp properties after model pulp recycling process including refining. Standard deviation are given in brackets.
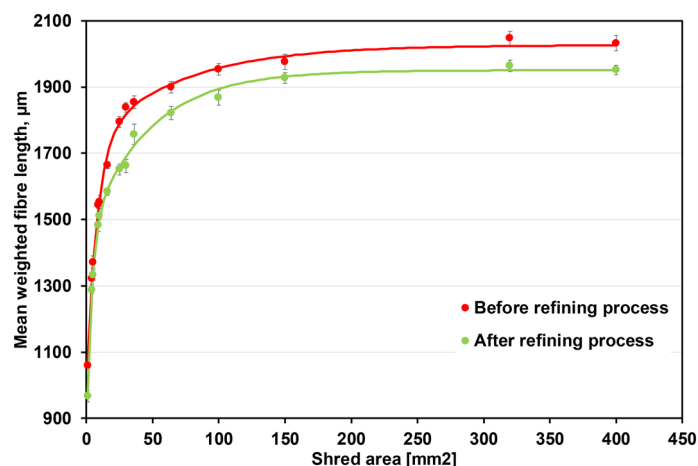

Figure 1. Average fibre length dependency on the cut surface area of samples (before and after model pulp recycling process including refining).

the results listed in Table 4 show that fibre length exerts a significant impact on the dynamic tensile properties of paper[54–56]. Importantly, in the case of fibre properties (Table 3 and Fig. 1), changes in the area of the shredded samples above 25 mm² did not significantly affect the tensile paper properties (Table 4). Based on this, it can be concluded that samples can be cut at 5 mm or larger without significant shortening of the fibres and no significant changes in pulp and paper properties. Therefore, the paper shredding provides useful wastepaper when performed in devices up to class P-6.

Research has shown that the fines fraction produced from fibres is responsible for slowing pulp-dewatering in the forming section of a paper machine[57,58]. The results obtained are fully consistent with those of earlier studies, in that the pulps with the highest fines content also have the highest SR freeness values (Table 2).

The air permeability of paper decreases as the SR freeness level increases[59–62], in agreement with previous results. The pulps characterised by lower average fibre length, and therefore, have improved barrier properties to gases even though their tensile properties are reduced (Table 4).

The roughness of paper increased with increasing initial fibre length, in agreement with previous results[34,61,63,64]. Therefore, the best smoothness results (230 mL/min) were obtained for paper produced from the pulp with the lowest fibre length. From the data provided, it can be concluded that this paper would likely have the best printability.

Microscopic images of the paper sheets, recorded using a Keyence VHX-6000 microscope equipped with a VH-Z100UR lens, are presented in Fig. 3. The fibres in the reference pulp (Fig. 3a) appear undamaged. The paper obtained from samples cut into 5×5 mm pieces (Fig. 3b) shows both undamaged fibres and cut fibres.
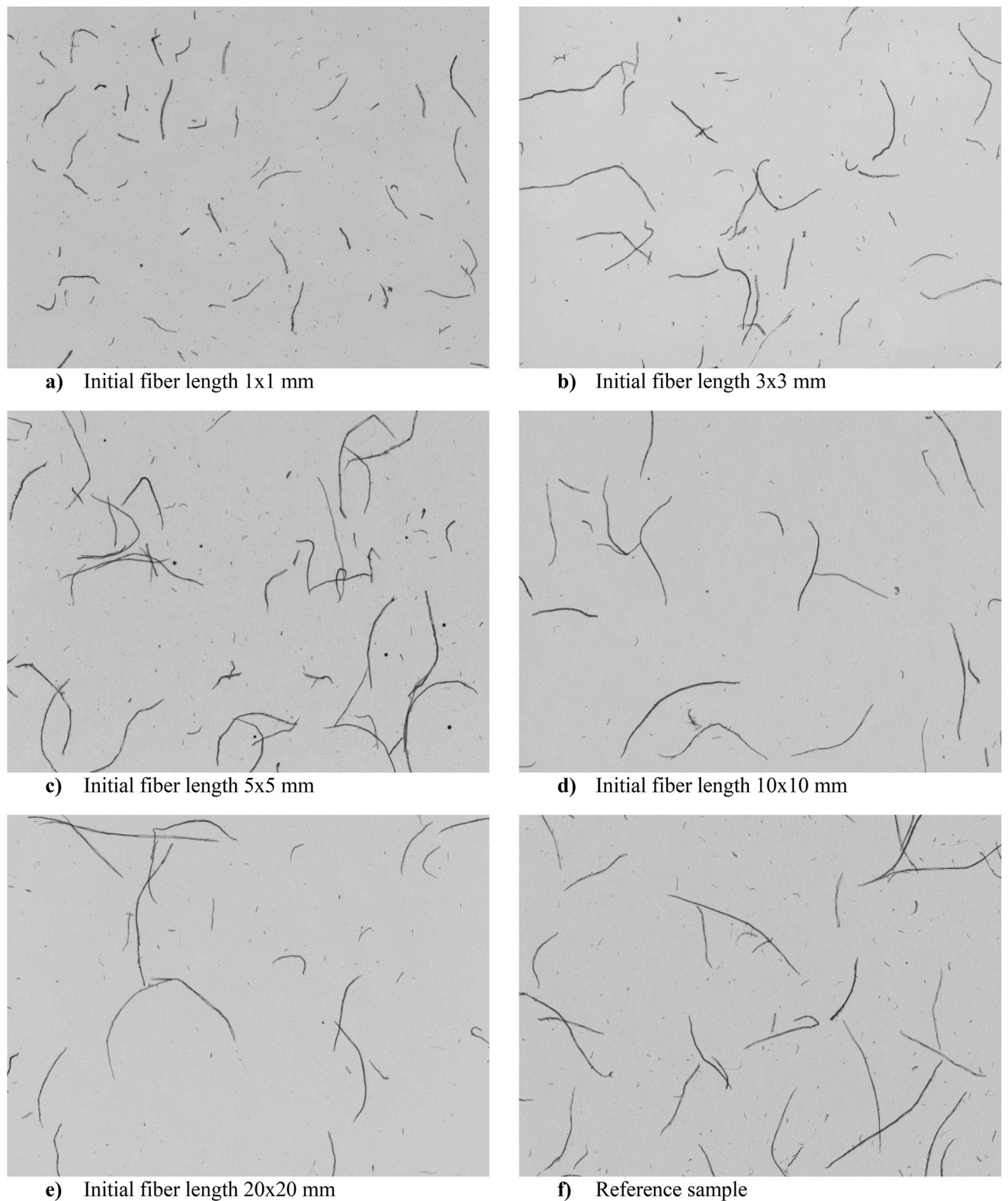
a) Initial fiber length 1x1 mm

b) Initial fiber length 3x3 mm

c) Initial fiber length 5x5 mm

d) Initial fiber length 10x10 mm

e) Initial fiber length 20x20 mm

f) Reference sample

Figure 2. Microscopic images of tested fibrous materials.

This observation clearly indicates that initial shortening of fibres damages the fibre structure to some extent, with an effect on average fibre length. However, these are local symptoms of shortening to a certain size. The vast majority of the fibres remain intact, as in the virgin pulp. Therefore, it can be concluded that shortening of fibres can be tolerated to a certain extent if the overall change to the fibre mixture is small.

An image from the sample with an initial size of 1×1 mm shows many damaged fibres (Fig. 3c), i.e., disintegration into finer material. Therefore, excessive fragmentation of the fibrous material causes considerable

Sample area	Force at break index	Stretch	Energy absorption index	Tensile stiffness index	Roughness	Air permeability
mm²	Nm/g	%	J/g	Nm/g	ml/min	ml/min
1	47.7 (0.8)	4.38 (0.01)	1.53 (0.07)	5116 (134)	230 (5)	156 (2)
4	57.9 (1.0)	4.43 (0.05)	1.80 (0.05)	5813 (146)	243 (3)	256 (2)
5	58.7 (0.9)	4.42 (0.03)	1.77 (0.04)	5866 (132)	251 (5)	252 (3)
9	69.0 (0.6)	4.30 (0.09)	2.05 (0.04)	5969 (118)	263 (8)	527 (4)
10	68.8 (0.5)	4.39 (0.08)	2.11 (0.03)	5963 (122)	269 (7)	533 (6)
16	70.6 (0.7)	4.21 (0.05)	2.15 (0.04)	6124 (147)	281 (6)	629 (3)
25	72.6 (1.1)	4.53 (0.02)	2.23 (0.05)	6334 (154)	290 (10)	857 (5)
30	73.2 (1.0)	4.44 (0.03)	2.20 (0.03)	6371 (139)	298 (8)	876 (6)
36	73.5 (0.3)	4.38 (0.06)	2.18 (0.02)	6384 (111)	301 (3)	954 (4)
64	74.0 (0.5)	4.23 (0.03)	2.24 (0.03)	6412 (125)	304 (7)	1201 (10)
100	74.5 (0.7)	4.45 (0.04)	2.20 (0.05)	6301 (108)	321 (8)	1315 (9)
150	74.6 (0.3)	4.36 (0.04)	2.16 (0.01)	6358 (111)	343 (5)	1354 (7)
320	74.6 (0.3)	4.42 (0.03)	2.19 (0.02)	6294 (130)	339 (6)	1418 (11)
400	74.5 (0.6)	4.32 (0.03)	2.15 (0.07)	6215 (149)	351 (10)	1415 (13)
Reference	74.6 (0.9)	4.61 (0.03)	2.20 (0.04)	6344 (151)	344 (8)	1421 (22)

Table 4. Mechanical properties of paper sheets produced from refined pulps. Standard deviation are given in brackets.
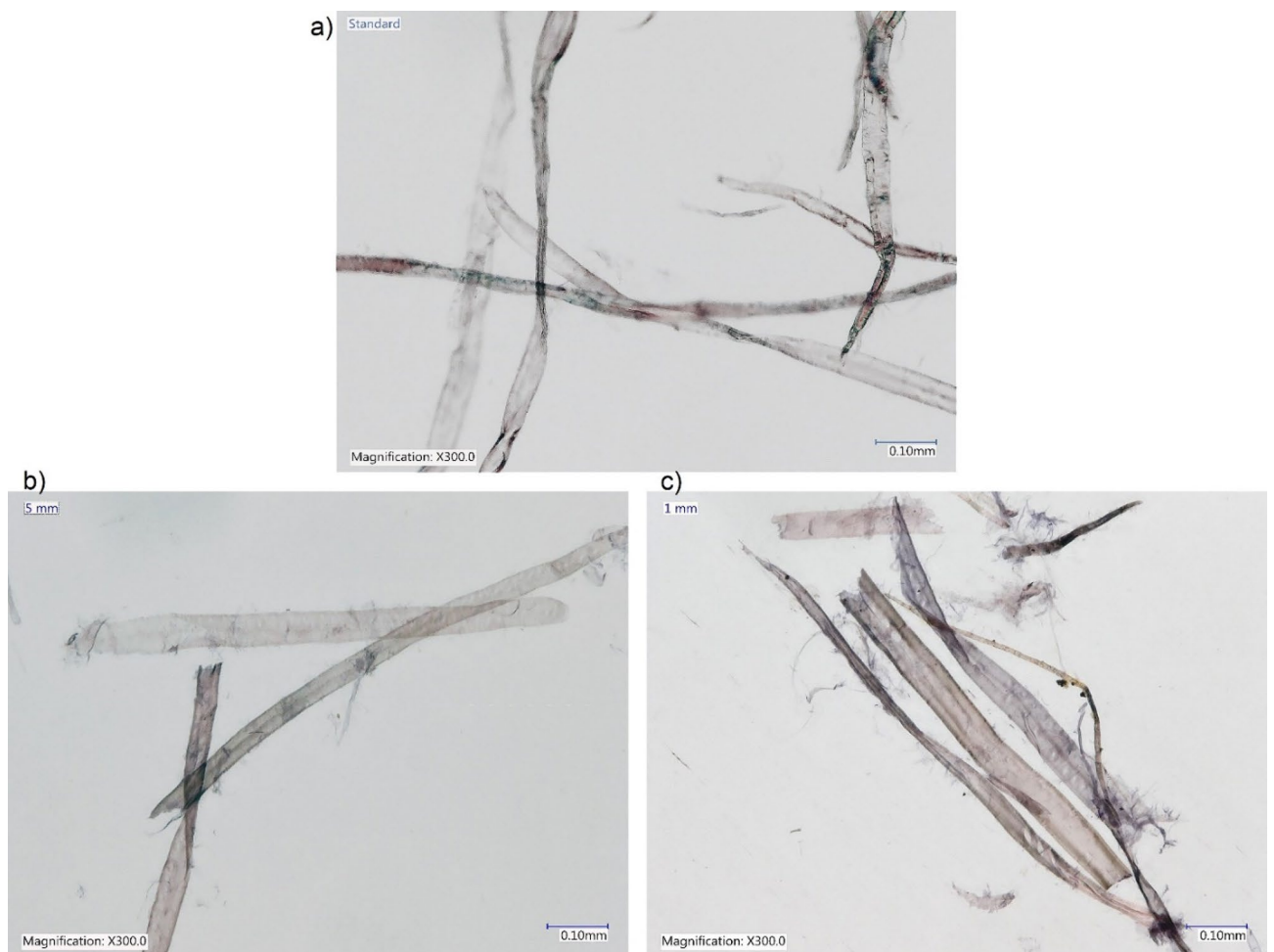

Figure 3. Microscopic images of paper sheets derived from (**a**) reference and (**b**, **c**) selected refined pulps produced from the tested fibrous materials.

damage to the fibrous fraction, and hence, deteriorates the potential of this fraction, which ultimately results in less desirable paper properties.

Based on the results obtained, the degree to which the shortened pieces of office waste paper can be converted into high-quality paper without any issues that reduce the value of the finished product can be predicted to a certain extent. From an ecological point of view, it is necessary to consider at the very least the issue of pulp freeness, and in turn, the energy needed for dewatering of the pulp. Excessive shortening of the paper samples worsens their dewatering capacity, as confirmed by the obtained results (Table 2). Therefore, the practice seeks to maintain a compromise and reduction of the refining range. Achieving efficiency in energy usage is considered the most cost-effective way to reduce CO_2 emissions[65]. Therefore, by producing waste office paper without undue fragmentation in shredder (if data security issues need not be considered), the properties of recycled paper products can be improved and the energy consumption can be reduced concurrently. Thus, the recycling of shredded paper can be carried out in a more ecological, environmentally friendly, and economic manner.

Conclusions

It was found in this study that the initial fibre length affects paper properties, the morphological characteristics of fibres, and the fine content of pulp, which in practice affects the cost of paper production. With other paper-making conditions held constant, paper samples produced from pulps with different initial fibre lengths showed various tensile properties. It is important to note that cutting paper into pieces with an area higher than 25 mm^2 in the shredding process does not significantly influence the properties of pulp or the tensile properties of paper made from the pulp. Cutting samples into pieces smaller than 25 mm^2, however, causes significant changes in the most important morphological parameters of the fibres and a sharp decrease in the dynamic and static strength properties of the paper with decreasing size of the shredded paper. Such a level of cutting is therefore unprofitable from a technological and an economic point of view because it required difficult pulp-dewatering processes and thus involves increased costs. The obtained results are therefore of great practical value because they demonstrate that the method of shredding paper in the shredder determines the processing potential of this pulp and the papermaking utility of the product. These conclusions can serve as a guide on how to responsibly shred paper, as well as to efficiently recycle fibres to manage biomass consumption.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Campbell, W. B. *The Cellulose-Water Relationship in Papermaking* (Dept Of Interior, Forest Service Bulletin, 1933).
2. Przybysz, K. & Wandelt, P. Pulp quality control system Part 3 Fiber strength. *Przeglad Pap.* **61**, 283–286 (2005).
3. Horn, R. A. *Morphology of Wood Pulp Fiber from Softwoods and Influence on Paper Strength. Research Paper FPL-242* (U.S. Department of Agriculture, 1974).
4. Joutsimo, O., Wathén, R. & Tamminen, T. Effects of fiber deformations on pulp sheet properties and fiber strength. *Pap. Puu-Pap. Tim.* **87**, 392–397 (2005).
5. Kerekes, R. & Senger, J. J. Characterizing refining action in low-consistency refiners by forces on fibres. *J. Pulp Pap. Sci.* **32**, 1–8 (2006).
6. Karlström, A. & Eriksson, K. Fiber energy efficiency. Part 2: Forces acting on the refiner bars. *Nord. Pulp Pap. Res. J.* **06**, 332–343 (2014).
7. Zeng, X., Retulainen, E., Heinemann, S. & Fu, S. Fibre deformations induced by different mechanical treatment and their effect on zero-span strength. *Nord. Pulp Paper Res. J.* **27**, 335–342 (2012).
8. Joutsimo, O. & Asikainen, S. Effect of fiber wall pore structure on pulp sheet density of softwood kraft pulp fibers. *BioRes.* **8**, 2719–2737 (2013).
9. Tingjie, C. *et al.* Effect of refining on physical properties and paper strength of pinus massoniana and china fir cellulose fibers. *BioRes.* **11**, 7839–7848 (2016).
10. Laine, C., Wang, X. S., Tenkanen, M. & Varhimo, A. Changes in the fiber wall during refining of bleached pine kraft pulp. *Holzforschung* **58**, 233–240 (2004).
11. Gharehkhani, S. *et al.* Basic effects of pulp refining on fiber properties: A review. *Carbohydr. Polym.* **115**, 785–803 (2015).
12. El-Sharkawy, K., Haavisto, S., Koskenhely, K. & Paulapuro, H. Effect of fiber flocculation and filling design on refiner loadability and refining characteristics. *BioRes.* **3**, 403–424 (2008).
13. Kerekes, R. Energy and forces in refining. *J. Pulp Pap. Sci.* **36**, 10–15 (2010).
14. O'Rourke, D. Nongovernmental organization strategies to influence global production and consumption. *J. Ind. Ecol.* **9**, 115–128 (2005).
15. Holik, H. *Handbook of Paper and Board* 2nd edn. (Willey-VCH, 2013).
16. Przybysz, K. Fibrillation of cellulose fibers. *Przemysl Chem.* **82**, 1149–1151 (2003).
17. Ferritsius, R. *et al.* Development of fibre properties in full scale HC and LC refining. in *2016 International Mechanical Pulping Conference, Jacksonville*, 26–28 (2016).
18. Kane, M. W. Beating, fiber length distributions and tensile strength-part. *Pulp Pap. Canada* **60**, 308–359 (1959).
19. Hartman, R. R. *Mechanical Treatment of Pulps for Property Development.* PhD Dissertation, Institute of Paper Science and Technology (1984).
20. Constable, M. The paper shredder: Trails of law. *Law Text Culture* **23**, 276–293 (2019).
21. Japanese Paper Recycle, *Paper Recycling Promotion Center* http://www.prpc.or.jp/document/publications/japan/.
22. Paper Recycling Facts, *University of Southern Indiana* https://www.usi.edu/recycle/paper-recycling-facts/.
23. Chauhan, V. S., Kumar, N., Kumar, M. & Thapar, S. K. Weighted average fiber length: An important parameter in papermaking. *Taiwan Lin Ye Ke Xue* **28**, 51–65 (2013).
24. Wangaard, F. F. & Woodson, G. E. Fiber length–fiber strength, interrelationship for slash pine and its effect on pulp–sheet properties. *Wood Sci.* **5**, 235–240 (1973).

25. Perng, Y. S., Wang, I. C., Cheng, Y. L. & Chen, Y. C. Effects of fiber morphological characteristics and refining on handsheet properties. *Taiwan Lin Ye Ke Xue* **24**, 127–139 (2009).
26. Choi, E. Y. & Cho, B. U. Effect of beating and water impregnation on fiber swelling and paper properties. *J. Korea TAPPI* **45**, 88–95 (2013).
27. Pruden, B. The effect of fines on paper properties. *Pap. Technol.* **46**, 19–26 (2005).
28. Kibblewhite, R. P. Interrelations between pulp refining treatments, fibre and pulp fines quality, and pulp freeness. *Pap. Puu-Pap. Tim.* **57**, 519–526 (1975).
29. Olejnik, K. Effect of the free swelling of refined cellulose fibres on the mechanical properties of paper. *Fibres Text. East. Eur.* **20**, 113–116 (2012).
30. Sundblad, S. *Predictions of Pulp and Paper Properties Based on Fiber Morphology*. Master Thesis in Macromolecular Materials, KTH Vetenskap Och Konst, Stockholm, Sweden (2015).
31. Retulainen, E. *The Role of Fibre Bonding in Paper Properties* (National Technical Information Service, Espoo, 1997).
32. Hietanen, S. E. K. Fundamental aspects of the refining process. *Pap. Puu-Pap. Tim.* **72**, 158–170 (1990).
33. Wang, X., Maloney, T. & Paulapuro, H. Fibre fibrillation and its impact on sheet properties. *Pap. Puu-Pap. Tim.* **89**, 148–151 (2007).
34. Lindqvist, H. *et al.* The effect of fibre properties, fines content and surfactant addition on dewatering, wet and dry web properties. *Nord. Pulp Pap. Res. J.* **27**, 104–111 (2012).
35. Kekäläinen, K., Illikainen, M. & Niinimäki, J. Morphological changes in never-dried kraft fibers under mechanical shearing. *Cellulose* **19**, 879–889 (2012).
36. Heymer, J. O., Olson, J. A. & Kerekes, R. The role of multiple loading cycles on pulp in refiners. *Nord. Pulp Pap. Res.* **26**, 283–287 (2018).
37. Vishtal, A. & Retulainen, E. Boosting the extensibility potential of fibre networks: A review. *BioRes.* **9**, 7933–7983 (2014).
38. Cheng, Q., Wang, J., McNeel, J. & Jacobson, P. Water retention value measurements of cellulosic materials using a centrifuge technique. *BioRes.* **5**, 1945–1954 (2010).
39. Scallan, A. M. & Carles, J. The correlation of the water retention value with the fibre saturation point. *Sven Papperstidning* **75**, 699–703 (1972).
40. Bäckström, M., Kolar, M. & Htun, M. Characterisation of fines from unbleached kraft pulps and their impact on sheet properties. *Holzforschung* **62**, 546–552 (2008).
41. Ferreira, P. J., Matos, S. & Figueiredo, M. M. Size characterization of fibres and fines in hardwood kraft pulps. *Part. Part. Syst. Charact.* **16**, 20–24 (1999).
42. Ciesielski, K. & Olejnik, K. Application of neural networks for estimation of paper properties based on refined pulp properties. *Fibres Text. East. Eur.* **5**, 126–132 (2014).
43. Paavilainen, L. Importance of particle size: fibre length and fines: for the characterization of softwood kraft pulp. *Pap. Puu-Pap. Tim.* **72**, 516–526 (1990).
44. Hai, L. V., Park, H. J. & Seo, Y. B. Effect of PFI mill and Valley beater refining on cellulose degree of polymerization, alpha cellulose contents, and crystallinity of wood and cotton fibers. *J. Korea TAPPI* **45**, 27–33 (2013).
45. Wathén, R. *Studies on Fiber Strength and its Effect on Paper Properties*. Dissertation for the degree of Doctor of Science in Technology, KCL Communications 11, Helsinki University of Technology (2006).
46. Motamedian, H. R., Halilovic, A. E. & Kulachenko, A. Mechanisms of strength and stiffness improvement of paper after PFI refining with a focus on the effect of fines. *Cellulose* **26**, 4099–4124 (2019).
47. Nordström, B. & Hermansson, L. Effect of fiber length on formation and strength efficiency in twin-wire roll forming. *Nord. Pulp Pap. Res.* **32**, 119–125 (2017).
48. Biermann, C. J. *Refining and Pulp Characterization. Handbook of Pulping and Papermaking* 138–139 (Academic Press, 1996).
49. Jang, H. F. & Seth, R. S. Determining the mean values for fibre physical properties. *Nord. Pulp Pap. Res. J.* **19**, 372–378 (2004).
50. Bajpai, P. *The Pulp and Paper Industry. Pulp and Paper Industry: Emerging Waste Water Treatment Technologies* 23–25 (Elesiver, 2017).
51. Fišerová, M., Gigac, J. & Balberčák, J. Relationship between fibre characteristics and tensile strength of hardwood and softwood kraft pulps. *Cell. Chem. Technol.* **44**, 249–253 (2010).
52. Johansson, A. *Correlations Between Fibre Properties and Paper Properties*. Master Thesis in Pulp Technology, KTH Vetenskap Och Konst (2011).
53. Sjöberg, J. & Höglund, H. Refining system for sack paper pulp: Part 1 HC refining under pressurised conditions and subsequent LC refining. *Nord. Pulp Pap. Res.* **20**, 320–328 (2005).
54. Larsson, P. T., Lindström, T., Carlsson, L. A. & Fellers, C. Fiber length and bonding effects on tensile strength and toughness of kraft paper. *J. Mater. Sci.* **53**, 3006–3015 (2018).
55. Watson, A. J. & Dadswell, H. E. Influence of fibre morphology on paper properties. Part 1: fibre length. *Appita J.* **14**, 168–178 (1961).
56. Horn, R. A. *Morphology of Pulp Fiber from Hardwoods and Influence on Paper Strength*. USDA Forest Service, Research Paper FPL 312, Forest Products Laboratory, 1–10 (1978).
57. Seth, R. S. The measurement and significance of fines. *Pulp Pap. Canada* **104**, 41–44 (2003).
58. Odabas, N., Henniges, U., Potthast, A. & Rosenau, T. Cellulosic fines: properties and effects. *Prog. Mater. Sci.* **83**, 574–594 (2016).
59. Sirviö, J. & Nurminen, I. Systematic changes in paper properties caused by fines. *Pulp Pap. Canada* **105**, 39–42 (2004).
60. Bossu, J. *et al.* Fine cellulosic materials produced from chemical pulp: The combined effect of morphology and rate of addition on paper properties. *Nanomaterials* **9**, 321 (2019).
61. Niskanen, K. (ed.) *Paper Physics, Papermaking Science and Technology, Book 16* (Finnish Paper Engineers Association and TAPPI, 1998).
62. Maloney, T. C., Todorovic, A. & Paulapuro, H. The effect of fiber swelling on press dewatering. *Nord. Pulp Pap. Res.* **13**, 285–291 (1998).
63. Fischer, W. J. *et al.* Pulp fines-characterization, sheet formation, and comparison to microfibrillated cellulose. *Polymers* **9**, 366–378 (2017).
64. Park, J. Y., Melani, L., Lee, H. & Kim, H. J. Effect of pulp fibers on the surface softness component of hygiene paper. *Holzforschung* **74**, 497–504 (2020).
65. Jonsson, D. K. *et al.* Energy at your service: Highlighting energy usage systems in the context of energy efficiency analysis. *Energy Effic.* **4**, 355–369 (2011).

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Author contributions

A.L. conceived the experiment(s), A.L. and M.D. conducted the experiment(s), P.P., E.M. and A.L. analysed the results, M.D. literature review, E.M. writing—original draft preparation, E.M. writing—review and editing, P.P. funding acquisition. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to E.M.

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