EFFECT OF FIBER FRACTIONATION ON REFINABILITY AND STRENGTH PROPERTIES OF WHEAT STRAW SODA-AQ PULP

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Beating studies for straw-based pulps showed that its freeness decreases faster than wood pulps. In other words, wheat straw requires considerably lower refining energy than wood-based furnish to reach the same level of freeness, due to higher content of primary fines and thinner fibers at lower cell wall thickness. The effect of fiber fractionation and then separate refining of long fiber fraction on refinability and strength properties of wheat straw soda-AQ pulp are discussed in this paper. Thus, soda-AQ pulp of wheat straw was fractionated, using a modified Bauer Mc-Nett fiber classifier having only a 50 mesh screen, into a long-fiber fraction (reject) and a short-fiber fraction (accept) at two different mass split ratios of LFR80 (80:20) and LFR60 (60:40). The refined long-fiber fractions were re-mixed with the related unrefined short fiber fraction, and their properties were determined in comparison with the control sample. The air resistance, tensile, and burst indices were improved by the fractionation treatments, especially in the case of LFR80, due to higher applied refining energy, which led to higher fiber to fiber bonding. By fractionation of wheat straw pulp and separate refining of longer fiber fraction, it is possible to increase PFI revolutions or refining energy to develop inter-fiber bonding strength without decreasing the tear index.

Keywords: Wheat straw; Soda-AQ pulp; Bauer Mc-Nett classifier; Refining

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INTRODUCTION

The continued growth in paper consumption as well as the emergence of bio-fuel will lead to an increased demand for wood and thus creating additional pressure on the diminishing forest resources. Increasing in demand of paper products, accompanied by constraints in wood fiber supply, is going to influence pulp prices and its availability in the near future (Goel *et al.* 2003, Tschirner *et al.* 2003). Some efforts at the national and international levels are ongoing to find suitable substitutes for wood fibers, which are commonly called as non-woods (Jahan *et al.* 2009).

Wheat straw produces good quality pulp for papermaking in terms of paper surface and strength properties (Sarkhosh *et al.* 2009). The thin and relatively short fibers of wheat straw contribute to the good formation and smoothness of the paper, which makes it desirable for writing and printing grades. Straw fibers are much more heterogeneous than wood fibers. It was reported that wheat straw contains 50% bast and sclerenchyma fibers, 30% parenchyma, 15% epidermal cells, and 5% vessels. These components vary considerably in terms of their length, diameter, cell wall thickness, and degree of delignification (Schott *et al.* 2003; Mackean and Jacobs 1997; Jacobs *et al.* 2000). The dimensions of wheat straw fibers are: average fiber length 1.18 mm, lumen diameter 5.68 µm, and cell wall thickness 3.96 µm. The dimensions of non-fibrous cells are: parenchyma 445×124 µm, vessels 96×57 µm, and epidermal cells 390×38 µm (Singh *et al.* 2011). Refining studies for wood and straw fibers showed that freeness decreases faster with wheat straw fibers than wood fibers, which is substantiated by the rapid drop in tear strength and a lower than usual increase in tensile and burst strength (Goel *et al.* 2003; Guo *et al.* 2009).

Refining is an important factor in papermaking process control and final paper qualities. One of the main purposes of refining is to obtain a higher sheet strength through development of fiber to fiber bonds. The amount and intensity of refining depend on the types of fibers, pulping method, and the required qualities of paper being made. A few investigations have been done to optimize the refining conditions of wheat straw pulps (Mackean and Jacobs 1997; Guo *et al.* 2009). They concluded that the sudden decrease in freeness of the wheat straw pulp could be due to an increase in primary fines with refining.

Vichnevsky *et al.* (2001) separated the main structural types of wheat straw APMP fibers and determined their effect on the physical properties of the straw mechanical pulp. They suggested that the fines removal should be considered depending on the targeted product. Guo *et al.* (2009) and Ljusgren *et al.* (2006) found that the fines from wheat straw pulps do not contribute to strength; therefore strength properties of straw pulp could benefit from fines removal. Heijensson-Hulten *et al.* (2012) suggested that the removal of fines from wheat straw pulps by fractionation improves bleachability and also drainage properties, while simultaneously the fines can be modified and used as a strength enhancer.

These studies demonstrated that the primary fines hinder strength improvement of straw pulp, so their complete removal may be beneficial to strength development. However, it has been suggested that the economics and alternative uses for the fines fraction would need to be examined.

The main aim of this study was to use the fractionation technique for partial removal of fine and short fiber fraction in order to increase refining potential of the fractionated long fiber pulps and improve the strength properties of the remixed soda-AQ pulp from wheat straw.

EXPERIMENTAL

Wheat straw was collected from the Golestan province in Iran. It was cut into 2 to 3 cm length pieces and washed quickly with tap water to remove the non-fibrous impurities. Washed samples were then air-dried and transferred into plastic bags and their moisture content was determined.

Pulping

The cooking experiments were conducted in a glycerin oil heated digester consisting six 2500 mL bombs. For each soda-AQ cook, 100 g (oven dry basis) wheat straw was used. The pulping was done at 160˚C for 30, 60, and 90 minutes using 16and18% sodium hydroxide plus 0.1% AQ to achieve the target kappa number of 20. The pulps were fully washed with tap water on a 200 mesh screen, and after being air dried, kappa number and total yield were determined according to T236 om-85 and gravimetrically, respectively.

Fiber Fractionation

The soda-AQ pulps were fractionated on a modified Bauer Mc-Nett fiber classifier, using only a 50 mesh screen, in order to separate the pulp components into two different fractions such as (a) short fiber fraction passed from 50 mesh screen as accept section (P50) and (b) long fiber fraction remained on 50 mesh screen as reject section (R50). Moreover, the target mass split ratios in fractionation trial were chosen to be 80:20 and 60:40, as long fiber to short fiber ratios (reject to accept ratios), and called as "LFR80" and "LFR60", respectively. In addition, long fiber fraction was called as LF80 and LF60, and short fiber fraction was called as SF80 and SF60, for LFR80 and LFR60 trials, respectively, throughout this paper.

The fractionation times of 5 and 10 minutes, after some preliminary trails, were selected to obtain the target mass split ratios of 80:20 for LFR80 and 60:40 for LFR60 samples, respectively. The proper amounts of fibers in each fraction were prepared by replicating the fractionation trials and collected for further treatments.

The OD weight percent of pulp passes through mesh 200 was defined as fine content and called as P200.

Refining

The pulps from the long fiber fractions, LF80 and LF60 samples, were refined by PFI mill to obtain different freeness levels of 420 and 350 mL, CSF according to TAPPI T248-sp standard. The refined pulps of LF80 and LF60 samples at any freeness were remixed with the belonging unrefined short fiber pulps of SF80 and SF60, respectively, at similar ratios as the original fractionation ratios of 80:20 and 60:40.

Handsheet Properties

Standard handsheets with a basis weight of 60 g/m² were made from the refined unfractionated control pulp and the remixed pulps of the fractionated samples for both LFR80 and LFR60 trials, according to TAPPI T205 sp-95. The paper properties were determined according to the related TAPPI standard methods. The data were analyzed using SAS statistical software. The results of handsheet properties were analyzed with factorial experiment in completely randomized design. Duncan test with 99% confidence level used for comparing and grouping the mean values.

RESULTS AND DISCUSSION

At a cooking temperature of 160 ˚C, different trials of pulping at various alkali charges and cooking times were done, and the results are shown in Table 2. On the basis of total yield, H-factor, kappa number, and uncooked fiber bundles or shive content of these pulps, run number 5 at kappa number of 20 was selected for further experiments.

Table 1. Cooking Conditions and Experimental Results of Pulping Process

Run	NaOH (%)	Time (min)	Yield (%)	H factor	Kappa number
1	18	90	47.7	677	15
2	18	60	49	477	16
3	18	30	50.2	287	18
4	16	90	50	677	17
5	16	60	51	477	20
6	16	30	53	287	25

Refining Response of Long Fiber Fractions

The initial freeness for unrefined control pulp, unrefined LF80 and LF60 pulp samples were 630, 660 and 680 mL, CSF, respectively, and their fiber distributions are shown in Fig. 1. The weight percent of fines (P200) and long fiber fraction (R50) were much lower and higher, respectively, in the long fiber fractions than the unfractionated original pulp, as has been reported in the literature (Mackean and Jacobs 1997b; Jacobs *et al.* 2000). However, the LF60 sample had slightly lower fines and higher long fibers than the LF80 pulp fraction, which confirm the relatively low efficiency of fine separation in fractionation process as was indicated by their almost similar initial freeness.

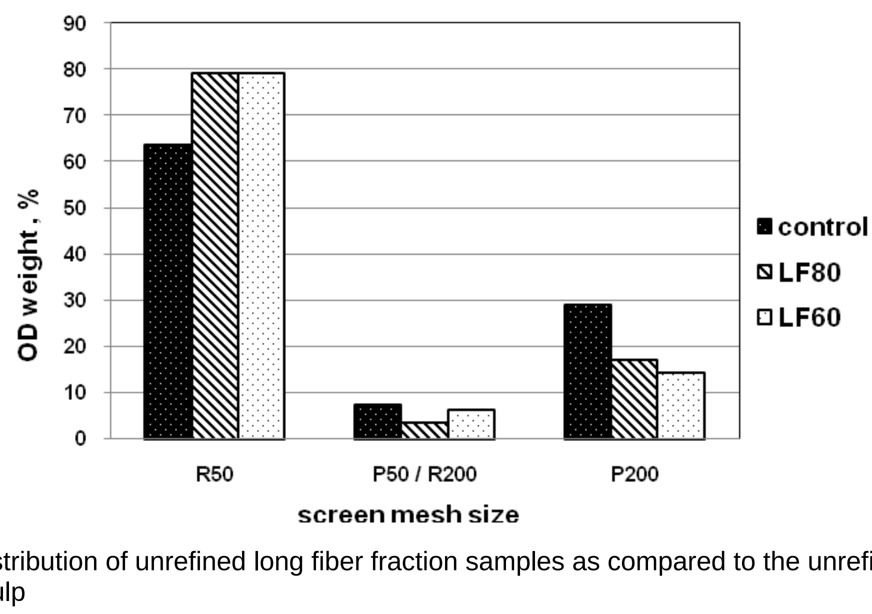

Fig. 1. Fiber distribution of unrefined long fiber fraction samples as compared to the unrefined control straw pulp

The refining response of long fiber fractions, LF80 and LF60, versus the original control straw pulp is shown in Fig. 2. It is quite clear that the long fiber fraction pulps, LF80 and LF60, need much higher PFI revolutions to reach a similar level of freeness, in comparison with original control pulp, due to higher initial freeness and higher amounts of long fiber and lower fine content.

The refinability of the pulp is defined as a general ability (ease) of certain pulp to change under refining action due to internal and external fibrillation and to some extent fiber cutting and fine formation, which is indicated as freeness drop per specific energy consumption or per specified refiner revolutions. The freeness drop in the LF80 fraction was slightly lower or similar to LF60 fraction due to the similar initial fiber distribution (see Fig. 1). However, the unfractionated control wheat straw pulp lost its freeness much more rapidly than the long fiber fractions, due to morphological characteristics of straw fibers such as low diameter and thin cell wall thickness (Mackean and Jacobs 1997a), higher primary fines parenchyma and epidermal cells and ease of secondary fine formation. Moreover, after pulping, part of the parenchyma and epidermal cells are not separated into individual cells and survive in the pulp as aggregates which could behave like small fibers. These agglomerates are often found in the long fiber fraction of wheat straw pulp. Upon refining, the agglomerates are broken into smaller cluster or individual cells which lead to higher primary fine formation and rapid freeness drop. The results are in accordance with Mackean and Jacobs (1997) and Roy *et al.* (1994).

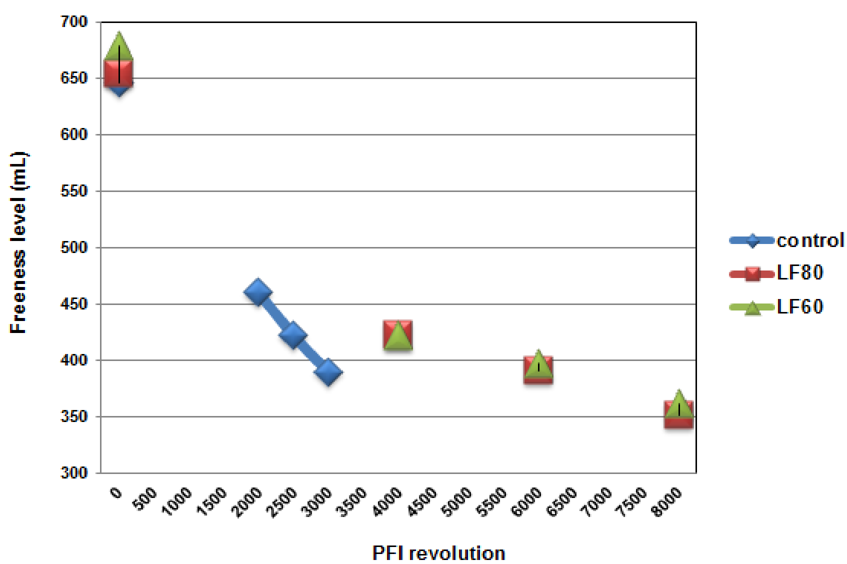

Fig. 2. Refining response of fractionated long fiber samples versus unfractionated control pulp

Effects on the Paper Properties

Both of the LF80 and LF60 pulp samples were refined to the target freeness levels of 400 and 340, and remixed with the related parts of unrefined pulps, SF80 and SF60, respectively, at any freeness level. The final freeness levels after remixing the LF and SF fractions are shown in table 2. The papermaking potentials of the fractionated and remixed pulp samples were compared with the original unfractionated control pulp at freeness level of 390 mL, CSF, to evaluate the effects of fractionation on the paper properties of straw soda-AQ pulp.

Table 2. Freeness Level of Remixed Pulps

Pulp sample	Initial freeness, mL, CSF	Refined freeness, mL, CSF	Remixed freeness, mL, CSF
LF80	654	400 mL	430
LF80	654	340 mL	350
LF60	678	440 mL	440
LF60	678	350 mL	350

Air resistance

The effects of two different levels of fiber fractionation, each refined to two different levels of freeness, on air resistance of paper are shown in Fig. 3. The air resistance of paper was increased by fractionation treatment. However, the air resistance was increased by decreasing the degree of fractionation, LF80 versus LF60, but increased by increasing the refining revolution or decreasing the refined freeness level, 340 versus 400 mL, CSF, as compared with original control sample at 390 mL, CSF. The higher refining revolutions especially in case of LF80 at 8000 refining revolutions, caused greater fiber deformation and higher fine formation as indicated by lower freeness and lead to higher apparent density and air resistance, in comparison with 3000 revolution in control pulp.

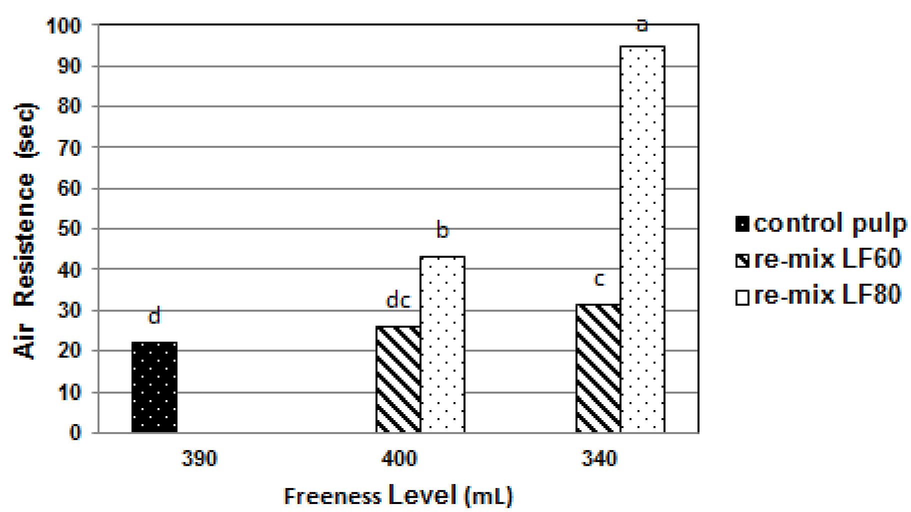

Fig. 3. Effect of fiber fractionation and refining degree on air resistance of paper

Strength Properties

Tensile and burst

The tensile and burst strength of a paper depends on both bonding degree and fiber strength, but predominately they are function of inter-fiber bonding degree (Panula-ontto 2002). The effects of two different levels of fiber fractionation, each refined to two different levels of freeness, on the tensile and burst strength of paper are shown in Figs. 4 and 5.

It can be seen that the tensile and burst strength of wheat straw soda-AQ pulp can be improved by the fractionation treatments especially in case of LFR80 (the split ratio of 80:20), due to higher applied refining energy, which led to higher fiber to fiber bonding, as was indicated by higher values of air resistance. However, the tensile and burst strength development in case of LFR80 (split ratio of 80:20) was greater than LFR60, due to higher share of the refined pulp (80 versus 60%) and more homogenous fibers at much lower share of unrefined pulp in the remixed sample, 20 versus 40%, respectively, which lead to reduce the inter-fiber bonding strength. This result is consistent with the findings of Guo *et al.* (2009) about the effects of wheat straw fines.

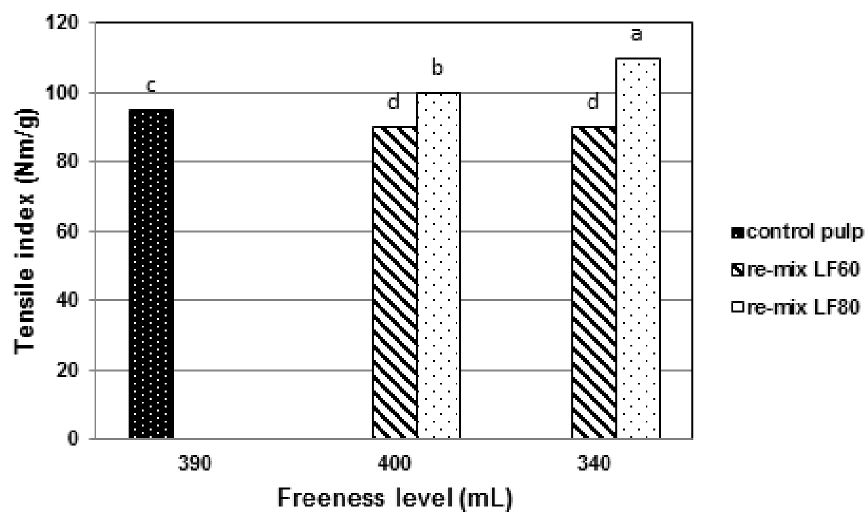

Fig.4. Effect of fiber fractionation and refining degree on tensile index

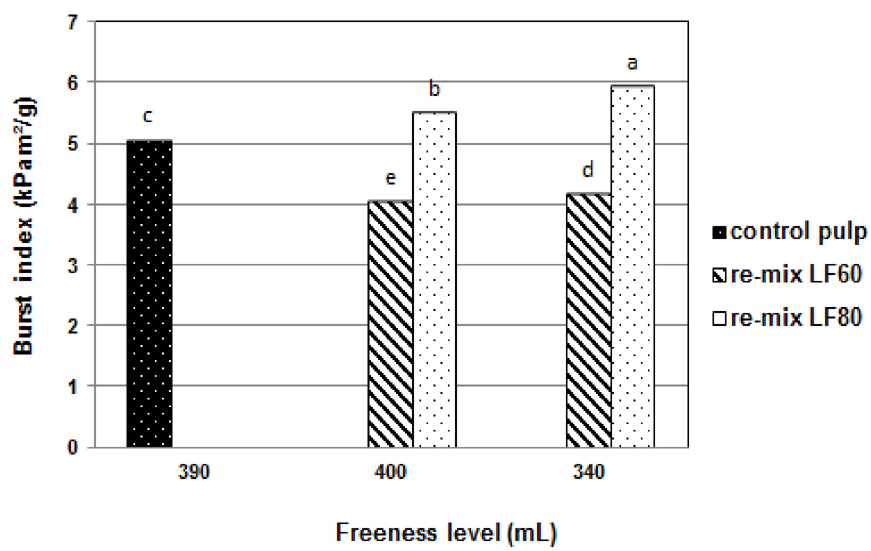

Fig.5. Effect of fiber fractionation and refining degree on burst index

Tear strength

The tear strength of a paper depends on fiber length, fiber strength, degree of inter-fiber bonding, and the fiber orientation in the paper. Longer and stronger fibers provide higher tear strength. At low levels of bonding, the degree of bonding determines the tear strength, but it is the fiber strength that determines tear strength at higher levels of bonding. Thus, tear strength increases in the initial stage of refining up to the point where the fibers are bonded so tightly that some of them are cut instead of being pulled out intact. An increase in fiber length increases the work needed to pull the fibers out from the sheet. The correlation between this work and the fiber length is high in pulps which are relatively poorly bonded; as the bonding degree increases the influence of fiber length decreases. Increasing in fiber coarseness or stiffness also leads to an increase in tear strength due to forming a looser sheet structure and therefore lower internal bonding strength and higher tear strength (Panula-ontto 2002)

The effects of two different levels of fiber fractionation, each refined to two levels of freeness, on tear strength of paper are shown in Fig. 6. The tear strength of wheat straw soda-AQ pulp of remixed stock from LFR80 and LFR60 (the split ratios of 80:20 and 60:40, respectively), were slightly lower or almost similar to the non-fractionated control sample, at similar refined freeness. The fact that the tear indices of these fractionated samples were close to control pulp indicates that by fractionation of wheat straw pulp and separate refining of longer fiber fraction, it is possible to increase PFI revolutions or refining energy to develop inter-fiber bonding strength without decreasing the tear index. However, the tear strength of these remixed stocks at lower freeness or higher refining revolutions (8000 versus 3000 revolutions), were much lower than the control sample, due to higher bonding strength, lower fiber length and higher fines as was indicated by higher burst and tensile strength and higher values of air resistance. The lower share of the refined pulp (60 versus 80 %) and higher share of unrefined short fiber fraction (40 versus 20 %, respectively) in the remixed sample of LFR60 lead to reduce the inter-fiber bonding strength and as a result higher tear strength in LFR60 in comparison with LFR80 remixed stock.

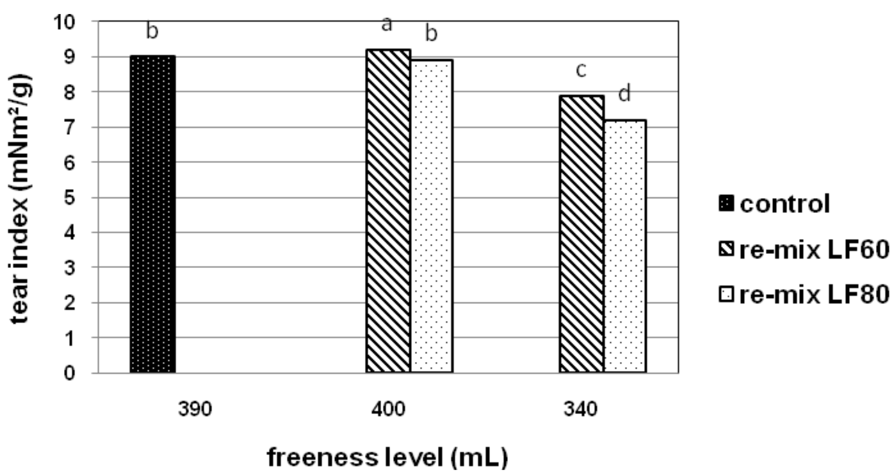

Fig. 6. Effect of fiber fractionation and refining degree on tear index

Effect of Refining after Remixing

The results of the above-mentioned fractionation trials showed that tensile and burst strength in the remixed stock of LFR60 (split ratio of 60:40) was much lower than LFR80, possibly due to higher share of the unrefined short-fiber fraction pulp (40 versus 20 %) which may cause a more non-homogenous fiber suspension that lead to reduced inter-fiber bonding strength. The effect of refining at relatively low mechanical action (1500 PFI revolutions) after remixing the refined long-fiber fraction of LF60 with the related unrefined short-fiber fraction of SF40, on the paper properties was investigated, and the results are shown in Table 3. It is clear that the refining treatment after remixing increased the air resistance of paper while the tensile, burst and tear strength were reduced. These results indicated that refining crushes wheat straw fiber and parenchyma cells which produced fines that act mainly as filler thus increased air resistance and reduced inter-fiber bonding and strength properties. These results were in good agreement with the findings of Mackean and Jacobs (1997b) and Guo *et al.* (2010).

Table 3. Effect of Refining after Remixing the Fractionated Stock of 60:40 Ratio on the Strength Properties

Properties / Pulp samples	Air resistance (sec)	Tear index (mN.m²/g)	Burst index (kpa.m²/g)	Tensile index Nm/g
remixed stock	31.6	9.08	4.18	90
remixed stock after refining	53.5	6.11	3.51	80

CONCLUSIONS

1. The long fiber fraction of wheat straw pulp required much higher PFI revolutions to reach a similar level of freeness, in comparison with the original control pulp, due to higher initial freeness and higher amounts of long fiber and lower fine content.
2. The tensile and burst strength development in case of LFR80 (split ratio of 80:20) was greater than LFR60, due to a higher share of the refined pulp (80 versus 60%) and more homogenous fibers at much lower share of unrefined pulp in the remixed sample, 20 versus 40%, respectively, which led to reduce the inter-fiber bonding strength.
3. The fact that the tear indices of these fractionated samples were close to control pulp indicates that by fractionation of wheat straw pulp and separate refining of the longer fiber fraction, it is possible to increase PFI revolution or refining energy to develop inter-fiber bonding strength without decreasing the tear index.

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REFERENCES CITED

Goel, A., Tschirner, U., Jewell, M., and Ramaswamy, R. (2003). "Comparison of refining response of soda-AQ and organosolv wheat straw pulps with traditional wood pulps," *Presentation at TAPPI Pulping/Process and Product Quality Conference Proceedings*, pp. 1071-1081.

Guo, S., Zhan, H., Zhang, C., Fu, S., Heijensson-Hulten, A., Basta, J., and Greschik, T. (2009). "Pulp and fiber characterization of wheat straw and Eucalyptus pulps- A comparison," *Bioresources* 4(3), 1006–1016.

Heijensson-Hulten, A., Basta, J., Samuelsson, M., Greschik, T., Ander, P., and Daniel, G. (2012). "Aspects on bleaching and tempo-mediated oxidation of wheat straw pulp fractions," *BioResources* 7(3), 3051-3063.

Jacobs, R., S., Pan, W., L., Fuller, S., W., and Mackean, W. T. (2000)."Wheat straw: Within-plant variation in chemical composition and fiber properties," *Presentation at TAPPI Pulping/Process and Product Quality Conference Proceedings*.

Jahan, M., Gunter, B., and Rahman, A. (2009). "Substituting wood with nonwood fibers in papermaking: A win-win solution for Bangladesh," Bangladesh development research working paper series (BDRWPS) No. 4(http://www.Bangladeshstudies.org).

Ljusgren, I., Wiberg, B., Tubek Lindblom, A., and Persson, T. (2006). "Papermaking potential of Scandinavian softwood pulp together with non-wood pulp," In: new technologies in non-wood fiber pulping and papermaking, 5th INWFPPC, Guangzhou, China, pp. 281-286.

Mackean, W. T., and Jacobs, R. S. (1997a). "Wheat straw as a paper fiber source," Unpublished Report, The Washington Clean Center Seatle, WA. USA, 1-47.

Mackean, W. T., and Jacobs, R. S. (1997b). "Refining of wheat straw pulp: A comparison with hardwoods," *Pulping Conference Proceedings*, TAPPI Press, Atlanta, pp. 667-672.

Panula-ontto, S. (2002). "Fractionation of unbleached softwood kraft pulp with wedge wire pressure screen and hydrocyclone," Licentiate of Science thesis, Helsinki University of Technology, Department of Forest Products Technology.

Roy, T. K., Subrahmanyam, S. V., Godyal, R. D., Panda, A., and Pant, R. (1994). "Effect of nonfiborous tissue on the papermaking properties of bagasse and straws," *IPPTA Convention Issue*, pp. 49-55.

Sarkhosh, F., and Talaiepour, M. (March 2009). "Soda-AQ pulping of wheat straw and its blending effect on old corrugated cardboard (OCC) pulp properties," M.Sc. thesis, Islamic Azad University, Science and Research Branch, Tehran, Iran.

Schott, S., Chausy, D., Mauret, E., Desloges, I., Anabela, A., Cordeiro, N., and Belghasem, M. (2003)."Valorisation of different agricultural crops in papermaking applications," *Pulp and Paper Science and Technology: Papermaking Science and Technology*. pp. 168-172.

Singh, S., Dutt, D., and Tyagi, C. H. (2011). "Complete characterization of wheat straw (*Triticumaestivum* PBW-343 l.emend. fiori and paol.) - A renewable source of fibers for pulp and paper making," *BioResources* 6(1), 154-177.

Tschirner, U., Ramaswamy, S., and Goel, A. (2003). "Effect of cereal straw fiber addition to papermaking furnish," *Pulp and Paper Canada* 104(10), 26-29.

Wichnevsky, S., and Chute, W. (2001). "Wheat straw pulp fractionation and their impact for the properties of mechanical pulp," TAPPI Pulping Conference Proceedings.

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