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

Fereshteh Fadavi,a,* Hossein Kermanian,a and Hossein Resalati b

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, Tschirmer 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.

Handsheets 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

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

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 unfractonated 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 un fractionated 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).

![Graph](image.png)

**Fig. 2.** Refining response of fractionated long fiber samples versus un fractionated 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 un fractionated 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

<table>
<thead>
<tr>
<th>Pulp sample</th>
<th>Initial freeness, mL, CSF</th>
<th>Refined freeness, mL, CSF</th>
<th>Remixed freeness, mL, CSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF80</td>
<td>654</td>
<td>400 mL</td>
<td>430</td>
</tr>
<tr>
<td>LF80</td>
<td>654</td>
<td>340 mL</td>
<td>350</td>
</tr>
<tr>
<td>LF60</td>
<td>678</td>
<td>440 mL</td>
<td>440</td>
</tr>
<tr>
<td>LF60</td>
<td>678</td>
<td>350 mL</td>
<td>350</td>
</tr>
</tbody>
</table>

**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](image)

**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

<table>
<thead>
<tr>
<th>Pulp samples</th>
<th>Properties</th>
<th>Air resistance (sec)</th>
<th>Tear index (mN.m²/g)</th>
<th>Burst index (kpa.m²/g)</th>
<th>Tensile index Nm/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>remixed stock</td>
<td></td>
<td>31.6</td>
<td>9.08</td>
<td>4.18</td>
<td>90</td>
</tr>
<tr>
<td>remixed stock after refining</td>
<td></td>
<td>53.5</td>
<td>6.11</td>
<td>3.51</td>
<td>80</td>
</tr>
</tbody>
</table>

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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