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Co-refining of wheat straw pulp and hardwood kraft pulp

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ABSTRACT

Wheat straw has been used as a pulping resource in China for many years. Wheat straw pulp (WSP) was widely used to substitute high quality chemical pulps such as those made from wood in producing writing and printing paper to reduce production cost of the resultant paper products and to improve paper smoothness without sacrificing paper strength. In this study, the process of co-refining of WSP and bleached hardwood kraft pulp (BHKP) was compared with the traditional separate refining and then blending these two pulps. The differences in refining energy consumption, the resultant pulp morphological and drainage properties, as well as the mechanical properties of the paper handsheets made of the resultant pulps were examined to explore the potential advantages of the co-refining process. The results show that the co-refining process has the potential to reduce refining energy consumption by at least 30% without affecting handsheet tensile and tear strength at a slightly lower re-wet tensile strength.

1. Introduction

China is one of the biggest agricultural countries in the world, and has abundant agricultural residues. Up to now the total utilization of the collected agricultural residues is still less than 40%, and only about 20 million tons of agricultural residuals have been used to produce paper products (Hu, 2008). As one of the post-harvest plants of seed crops, wheat straw is a valuable and renewable bioresource that can yield 110 million tons per year in China (Yang & Wang, 1999). Except that some of them were used to make paper or as feedstuff for livestock, most of them were set on fire or discarded as environmental pollutants (Yang & Wang, 1999). Wheat straw pulp (WSP) that accounts for 70–75% of the total pulp production from agricultural residues is mostly used for making printing and writing paper products (Zhong, 2004). The demand for wheat straw to be used in China paper industry is reported approximately 80 million tons per year, which indicates that approximately 30 million tons WSP can be produced (Chen & Pang, 2008). From the economic and environmental side of view, WSP will have an attractive future.

Besides its low production cost comparing with wood pulp (Cao, Cao, & Kuang, 2003), WSP also has other advantages such as low refining energy consumption, good sheet-formation and interfiber bonding (Guo et al., 2008; Xu, Zhai, & Leng, 2008; Yu, Kettunen, & Paulapuro, 2000). Banavath, Bhardwaj, and Ray (2011) compared the effect of refining time on pulp freeness of various wood and non-wood pulps, demonstrating that WSP was the easiest to refine, compared to softwood pulp followed by bamboo, hardwood and bagasse pulps. Therefore, WSP can be used to reduce overall production cost and improve paper surface and strength properties of various paper products (Gong, 2008; Zhang, He, & Ni, 2011;). Zhang et al. (2011) showed that with an addition of 5–10% well-refined bleached WSP, the tensile strength of the test sheets made of mixed bleached WSP and bleached chemi-thermo-mechanical pulp (BCTMP) can be increased by 10–20% without sacrificing pulp handsheet bulk. Similar results were obtained by adding the refined bleached WSP into a mixed furnish of bleached kraft pulp and BCTMP.

The typical mill practice is to refine WSP and bleached hardwood kraft pulp (BHKP) separately and then combine them in paper furnish in the machine chest. WSP is usually slightly refined in order to avoid a significant drop in drainage while BHKP is refined for strength and surface properties. Several researches on co-refining of bleached WSP and P-RC APMP (preconditioning followed by refining chemical treatment, alkaline peroxide mechanical pulp) or white birch and black spruce mixture have shown that it can produce synergistic effects on the optical and mechanical properties of the blended furnish. Many laboratory- and large-scale trials have demonstrated that the co-refining process can reduce refining duration, preserve fiber length, and result in better tensile energy absorption (TEA) and physical strength in comparison with the separate refining process (Gao, Huang, Rajbhandari, Li, & Zhou, 2009; Xu, Zhai, & Xu, 2010). Brindley and Kibblewhite (1996) demonstrated that the mixed hardwood:softwood blends would have freeness and strength properties similarly developed whether separately refined or co-refined at 0.5 W s/m specific

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edge load, whereas co-refining at 1.5 W s/m would give inferior results.

So far, the studies on co-refining have concerned mainly in WSP blended with HYP (Xu et al., 2010). No results are available in the literature on the co-refining of BHKP with WSP. It is not clear how the co-refining affects the pulp fiber morphology and the resultant pulp mechanical properties such as tensile strength and tear strength. Furthermore, it is unclear whether co-refining would save refining energy when WSP is blended and then co-refined with BHKP.

The objective of this study is to investigate the differences between the co-refining and separate refining processes for WSP and BHKP, in terms of the pulp beatabilities, fiber morphology, and the mechanical properties of paper handsheets made of the resultant pulp samples.

2. Experimental

2.1. Materials

The wet bleached WSP sample (beating degree of 33° SR and brightness of 65.1% ISO) was collected at a pulp mill in Shandong province, China. The collected pulp was stored in the cold room at 4 °C. The market bleached eucalyptus kraft pulp sheets (beating degree of 16.5° SR and brightness of 87.0% ISO) imported from Canada were used as a BHKP sample.

2.2. Disintegration of pulp

30.0 ± 0.5 g (oven dry weight) WSP was diluted using 2000 mL deionized water and disintegrated in a standard disintegrator (Model 1107, Lorentzen & Wettre Co. Ltd., Sweden) for 30,000 revolutions at room temperature. 30.0 ± 0.5 g (oven dry weight) eucalyptus pulp sheets were soaked thoroughly in 500 mL deionized water at room temperature in a plastic beaker for 4 h before being disintegrated using the same procedure. The two disintegrated pulp samples were both adjusted to a mass fraction of 10% following the TAPPI T248 sp-00 (2002). The co-refining pulp samples were prepared by first blending the BHKP with WSP samples at given blending ratios, and then soaking and disintegrating as the same procedure as the BHKP sheets.

2.3. Separate refining

The disintegrated BHKP samples were first refined in a Mark-VI PFI mill (Oslo, Norway) according to TAPPI T248 sp-00 (2002) for 3000, 6000, 9000, 12,000 and 20,000 revolutions, respectively. Then the Schopper–Riegler beating degrees of refined BHKP samples were measured according to the ISO 5267-1 (1999). Finally the disintegrated WSP samples were refined until reaching to the same beating degrees as the refined BHKP samples, respectively.

2.4. Blending ratios of pulp samples and following co-refining

In order to explore the potential advantages of co-refining for WSP and BHKP, the collected samples were mixed in blending ratio of 7:3 and 3:7 for BHKP:WSP, respectively. In the separate refining experiment, WSP and BHKP samples were blended after being refined, and these samples were named as SR7/3 and SR3/7 (the former digit represents BHKP share); correspondingly, in the co-refining experiment these two samples were blended before being refined, and yielded samples were named as CR7/3 and CR3/7 (similarly, the former digit represents BHKP share).

The well blended and disintegrated co-refining pulp samples were refined until reaching to beating degree 35°, 50°, 65° and 80° SR, respectively, by using a PFI mill following the TAPPI T248 sp-00 (2002).

2.5. Fiber quality analysis

The fiber morphology of each pulp sample was analyzed. Approximately 0.1–0.2 g of oven-dry weight pulp sample was tested using a Fiber Tester (Model 912, Lorentzen & Wettre Co. Ltd., Sweden).

2.6. Pulp drainage property test

The drainage of each pulp sample was measured using a Drainage Freeness Retention Tester (DFR-04, BTG International Co. Ltd., Germany). 1000 mL fiber suspension of 20.0 ± 0.5 °C with consistency 0.2% ± 0.002% was poured into the tester and stirred at 700 rpm. The volumetric amount of filtrate collected at 10 s was recorded.

2.7. Paper handsheets preparation and test

Paper handsheets of 60 ± 2 g (oven-dry weight)/m^2 were prepared according to the TAPPI T205 sp-02 (2002). In addition, tensile strength and tear strength of the handsheets were tested according to the TAPPI T494 om-01 and T414 om-98 (2002), respectively, after being conditioned at temperature 23 ± 1 °C and relative humility 50 ± 2% for more than 4 h.

2.8. SEM analysis

A scanning electron microscope (SEM) (Model JSPM-56380LV, Japan Electron Optics Laboratory Co., Ltd.) was used to analyze the surface morphology of the handsheets.

2.9. Re-wet tensile strength test

Re-wet tensile strength of paper handsheets was tested by using a Thwing-Albert tensometer (Thwing-Albert Co. Ltd., USA). The prepared handsheets were cut into strips with a width of 15 mm, and then the strips were curled to make the two ends meet, the middle part of the strips was dipped into distilled water at 23 ± 1 °C for 8 min to be fully saturated. The strips were then taken out and sandwitched between two 3-layer industrial filter paper. Free water on the strips was removed by lightly tapping the sandwitch and finally the strip tensile force was tested according to the TAPPI T456 om-03 (2002).

3. Results and discussion

3.1. Refining curves of different pulps and refining energy consumption

The relation between PFI mill revolution and pulp beating degree represents the susceptibility of pulp to refining. As shown in Fig. 1, WSP was easier to be refined than BHKP. For instance, BHKP gained a beating degree of only approximately 6° SR at 3000 revolutions. The beating degree of BHKP reached almost 82° SR after 20,000 revolutions. However, WSP could be easily refined to 82° SR after 4200 revolutions. Even though the initial beating degree of WSP (33° SR) was much higher than that of BHKP (16.5° SR), the net beating degree gain per revolution of WSP was much higher than that of BHKP.

Blending WSP with BHKP can facilitate refining as expected. The number of refining revolutions required for the CR7/3 (30% WSP) was only approximately 50% of that for the pure BHKP to reach the same beating degree. Increase WSP in the mixture to 70%, i.e.,

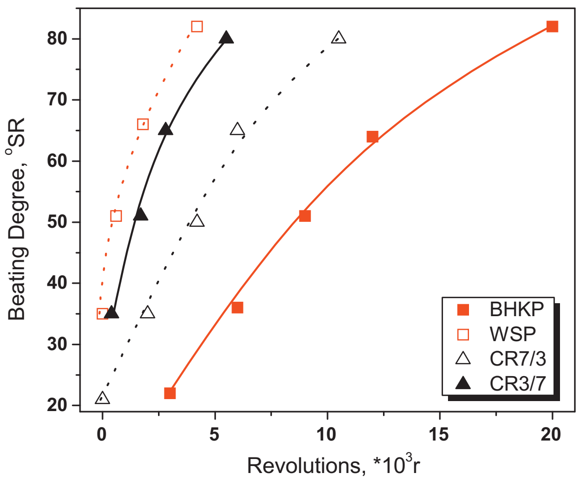

Fig. 1. Refining curves of different pulps.

Table 1
Effect of refining energy consumption savings of co-refining pulps.

Constituents	CR7/3	SR3/7
35° SR		
Weighted revolutions, *r*	4200	1800
Revolutions needed, *r*	2000	400
Revolutions savings, %	52.4	77.7
50° SR		
Weighted revolutions, *r*	6480	2880
Revolutions needed, *r*	4200	1700
Revolutions savings, %	35.2	69.4
65° SR		
Weighted revolutions, *r*	8940	4860
Revolutions needed, *r*	6000	2800
Revolutions savings, %	32.9	42.4
82° SR		
Weighted revolutions, *r*	14,900	8100
Revolutions needed, *r*	10,500	5500
Revolutions savings, %	29.5	32.1

Note:
1. The *weighted revolutions* = pure BHKP revolutions * BHKP fraction + pure WSP revolutions * WSP fraction.
2. *Revolutions needed* are the revolutions actually used when the pulp samples were refined to the desired beating degrees.
3. Revolutions savings = (weighted revolutions − revolutions needed)/weighted revolutions * 100%.

CR3/7, the mixed pulp became even easier to be refined. To qualitatively estimate the effect of co-refining on savings of refining energy, the weighted revolutions (that is, the predicted co-refining revolutions needed for the blended furnish) were calculated, and compared with the actual revolutions required to refine blended furnish to the desired beating degrees. The refining revolutions savings can be clearly seen in Table 1. For the blended sample with 70% BHKP, CR7/3, to reach the beating degree of 50° SR, the number of actually needed refining revolutions was 4200, while the number of weighted revolutions needed was 6480. This is roughly 35% reductions in refining revolutions. The actual refining revolutions was only 1700 for the blended sample with 30% BHKP or 70% WSP, CR3/7, very close to the revolutions for the 100% WSP sample.

3.2. Effect of co-refining on drainage property of pulp

The dynamic drainage capacity of pulp, which is affected by the fibrillation of fiber and by the amount of fines, represents pulp drainage property in addition to pulp beating degree. Generally speaking, the lower the pulp beating degree, the better is the pulp drainage capacity. As shown in Table 2, the dynamic drainage capacity of BHKP was always better than WSP, and the dynamic drainage capacity of the blended furnish with a low WSP content was better than that with a high WSP content. Mixing BHKP with WSP could result in a blended furnish with an improved dynamic drainage capacity. For WSP, the dynamic drainage capacity was 310 g at the beating degree of 35° SR. While mixing 70% BHKP with 30% WSP, CR7/3, of about 32% increase in the dynamic drainage capacity was obtained. Whereas mixing 30% BHKP with 70% WSP, that is, CR3/7, the dynamic drainage capacity was 347 g, meaning that only about 12% gain in the dynamic drainage capacity was yielded.

Table 2
Effect of co-refining on dynamic drainage property of blended furnish.

Constituents	Dynamic drainage capacity, *g*			
	BHKP	WSP	CR7/3	CR3/7
21° SR	603	–	613	–
35° SR	439	310	408	347
50° SR	330	208	262	229
65° SR	228	170	220	182
80° SR	153	127	154	139

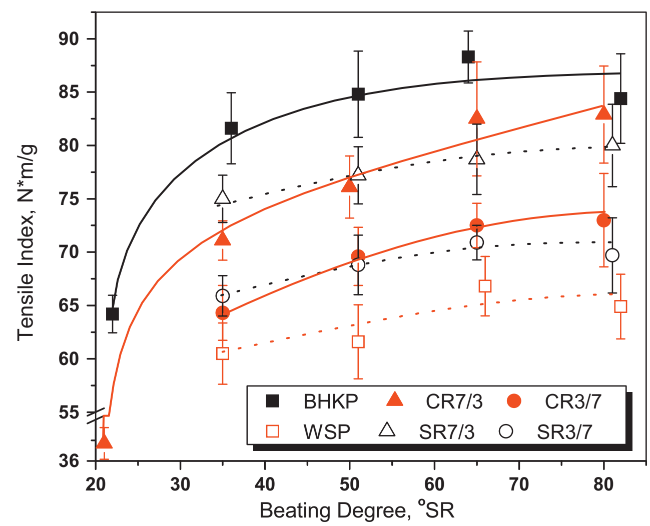

Fig. 2. Effect of co-refining on tensile strength of handsheets.

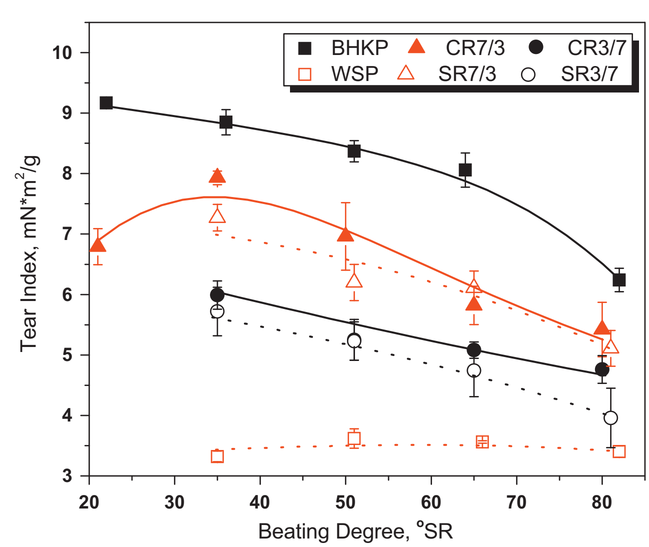

Fig. 3. Effect of co-refining on tear strength of handsheets.

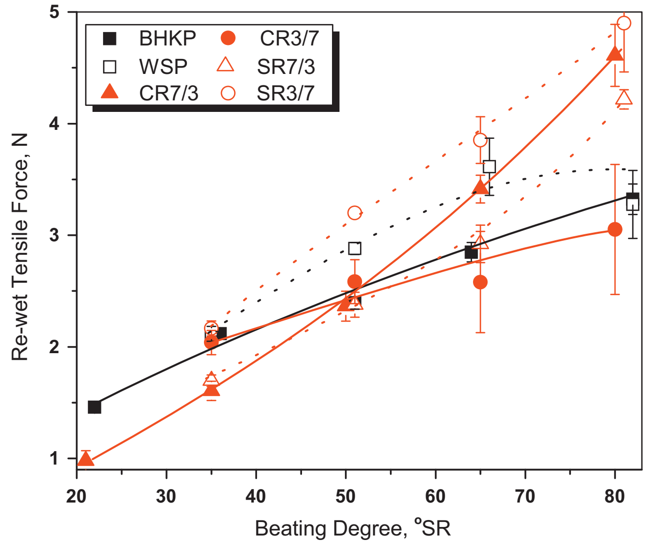

Fig. 4. Effect of co-refining on re-wet tensile strength of handsheets.

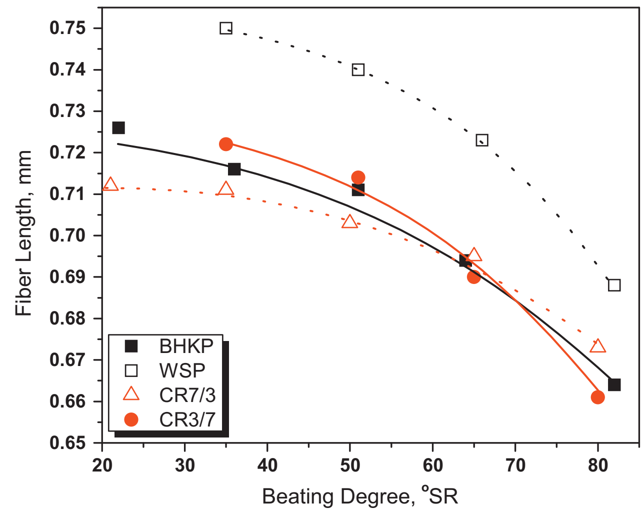

Fig. 5. Effect of co-refining on pulp fiber length.

3.3. Effect of co-refining on pulp tensile and tear strength

The standard paper handsheets were made to study the effect of co-refining on strength properties of the blended pulps. It can be observed in Fig. 2 that the tensile strengths of the co-refining samples (CRs) and separate refining samples (SRs) at the same blending ratios were almost the same, especially within the beating degree range from 40° SR to 60° SR, demonstrating that co-refining would not affect the strength properties of the resultant pulps. Furthermore, the tensile strength of CRs with a high BHKP content was better than that with a low BHKP content, i.e., the tensile strength of CR7/3 was better than that of CR3/7.

Tear strength, which is one of the most important strength properties for pulp or paper, can be mainly affected by fiber length (Casey, 1980; Zhang et al., 2011). As shown in Fig. 3, the tear strength of WSP was lower than that of BHKP, and no apparent changes were found as refining proceeded. The tear strength curves of CRs and SRs were all falling between the tear strength curves of WSP and BHKP. The tear strengths of CRs and SRs were about the same under the same beating degrees. Furthermore, the tear strength of the blended pulp with a high BHKP content was better than that with a low BHKP content.

3.4. Re-wet tensile strength property of blended pulp

The re-wet tensile strength is used to characterize the stretching resistance of water-saturated paper, which can be also used to estimate the coating machine runnability when the paper tends to be used in a damp environment. As shown in Fig. 4, WSP had a relatively higher re-wet tensile strength than BHKP. The SR3/7 (70%

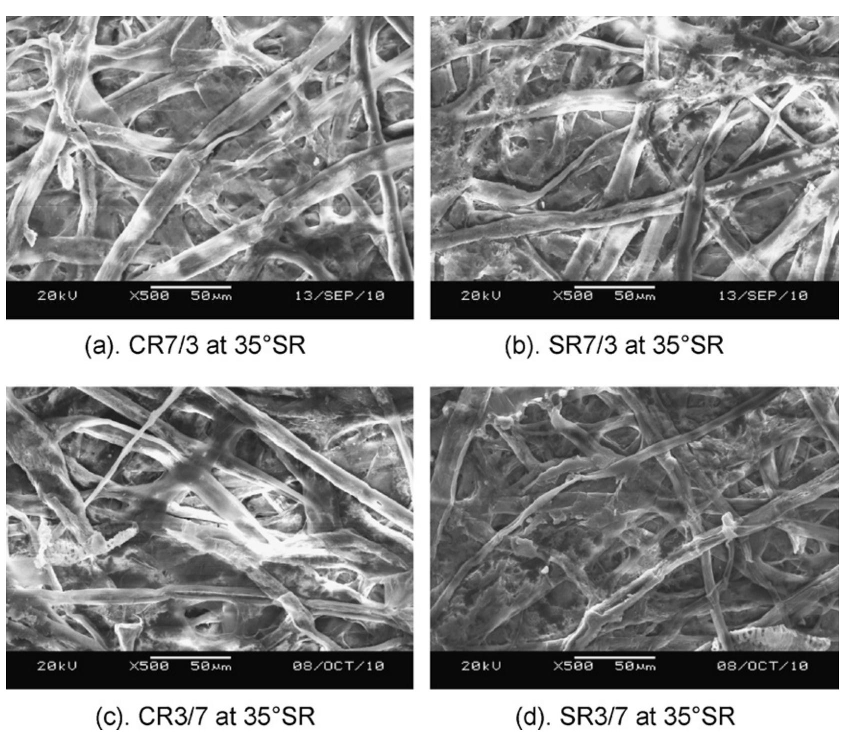

Fig. 6. SEM analysis of CRs and SRs.

WSP) had a higher re-wet tensile strength than the corresponding CR3/7 especially at beating degrees greater than 50° SR. This trend was reversed at a high HW content, i.e., the re-wet strength of SR7/3 was lower than CR7/3 at beating degrees greater than 50° SR.

3.5. Fiber quality analysis

The effect of co-refining on fiber length of the blended pulps is shown in Fig. 5. In Fig. 5, where pulp fiber length is represented as a function of beating degrees, the fiber length for BHKP, WSP, and their co-refining pulps declined with the increase of pulp beating degree. WSP and BHKP had roughly the same fiber length before refining treatment, whereas the fiber length of their co-refining samples was so close to that of BHKP after refining treatment. This demonstrates that the cutting or shortening for WSP fibers might be more obvious than BHKP. Moreover, the fiber length of co-refining samples going towards that of BHKP is also a certification of which WSP is easier to be refined than BHKP.

3.6. SEM analysis of test sheets

To further explore the effect of co-refining, a series of the test sheets made of CRs and SRs with the same blending ratios were subjected to SEM analysis. The results indicated that, at the same BHKP or WSP content, more debris appeared in SRs than in CRs, i.e., the SR3/7 (Fig. 6b) and SR7/3 (Fig. 6d) had more amount of fragments than the corresponding CR3/7 (Fig. 6a) and CR7/3 (Fig. 6c), respectively. The fragments were mostly produced from WSP during refining. This is attributed to the easier refining for WSP than wood pulps because WSP is friable itself and, consequently, easy to bring fragments while refining especially separate refining (Lei, Huang, Li, Huang, & Yu, 2010; Liu, Li, Qin, Zhang, & Zhao, 1984).

4. Conclusions

The co-refining of WSP and BHKP has a potential to reduce refining energy consumption by at least 30% without sacrificing pulp tensile and tear strength. The amount of refining energy savings would grow as the WSP content increased.

The tensile strengths of CRs and SRs at the same blending ratios were almost the same, and the tensile strength of CRs with a high BHKP content was better than that with a low BHKP content.

Both WSP content and beating degree would influence the re-wet tensile strength of the co-refining pulps. The fiber length of the co-refining pulps had almost the same trend varying with beating degree as BHKP.

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