Substitution of hardwood kraft with aspen high-yield pulp in lightweight coated wood-free papers: Part I. Synergy of basestock properties

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ABSTRACT: We conducted a systematic investigation of the effects of substituting high-yield pulp (HYP) for hardwood bleached kraft pulp (HBKP) on the properties of basestock, coated, and calendered sheets, with a focus on lightweight coated grades. The results are reported in two parts. In this first part, we focus on the potential effects of HYP substitution on basestock properties. Experimental results show that although HYP substitution increases bulk, it has no negative effect on roughness and air resistance. A surprising finding is that although HYP alone has much lower strength properties than HBKP, partial substitution of HBKP by HYP actually increases the tensile strength of a lightweight sheet, indicating a synergy between HYP and kraft pulps. This is explained by the improved inter-fiber bonding. Substitution by HYP also has positive effects on properties such as bending stiffness, internal bond strength, elastic modulus and formation. Other properties, such as tear index, burst index, MIT double folds, dimensional stability, stretch, and tensile energy of absorption were maintained.

Application: These results suggest that the substitution of HBKP with aspen HYP up to 30% is technically feasible and even beneficial for producing a lightweight "wood-free" basestock.

Lightweight coated (LWC) wood-free papers are used mostly for high-speed heatset web offset (HSWO) color printing. With a low basis weight and low coat weight, the strength, surface, and structural properties of the LWC wood-free paper are all important for achieving good runnability and high print quality [1]. For example, lower tensile strength and stretch may lead to web breaks, while lower internal bonding strength may lead to blistering and delamination. Low opacity, poor coating coverage, and surface smoothness can lead to poor print quality.

In traditional wood-free coated papers, hardwood bleached kraft pulp (HBKP) and softwood bleached kraft pulp (SBKP) are the main furnishes. The choice of which to use depends on the desired end-use requirements. Generally, SBKP is used to provide strength and runnability due to its long fibers and high bonding ability. HBKP gives good surface smoothness due to its short fiber length and narrow fiber length distribution [2]. The content of SBKP in wood-free basestock typically ranges from 5% to as high as 50% (the rest is HBKP in the range of 50% to 95%).

Recently, papermakers have shown an increasing interest in substituting HBKP with high-yield pulps (HYP) as a cost-effective way of improving their product performance [3-6]. This is because HYP can be made in strength and brightness similar to HBKP, but with other unique features, such as high bulk, large surface area, and high fines content.

HYP was first produced with sulfite-treated chemithermomechanical pulping, traditionally called CTMP or BCTMP, followed by the development of alkaline peroxide-based TMP pulps. However, the predominant process for HYP is BCTMP where the chips are sulfite pretreated at the impregnation stage and then refined. After refining, the pulp is bleached to a high ISO brightness of 85%. Depending on the end uses, the bulk and strength properties of the HYP can be modified by changing the amount of alkali used and refining energy [4].

Numerous studies have tried to gain a better understanding of the properties of HYP from various hardwood species, such as beech, birch, maple, eucalyptus, aspen, and even nonwood raw material [7-12]. Some papermaking-related issues of using HYP were also investigated, including the presence of dissolved and colloidal substances in HYP and their effect on the sizing behavior [13-15]. Among various wood species, aspen HYP has been the main choice as substitute for HBKP in LWC wood-free papers. In spite of the many studies of the properties and application of HYP, concerns remain about the effects of HYP substitution in coated wood-free papers because HYP is essentially a chemimechanical pulp. The remaining issues are summarized below:

Does substituting HYP for HBKP reduce the sheet strength? — In comparison with HBKP, the fibers of the aspen HYP are typically shorter and significantly coarser. As a result, a higher bulk and lower sheet strength can be expected when substituting HBKP with aspen HYP to produce a basestock [16-17]. One study showed that aspen HYP is suitable for producing low strength and high bulk grades [18]. On the other hand, Xu and Zhou recently reported that a combined pulp of HBKP and aspen HYP had a higher tensile, tensile energy absorption, and stretch than the weighted contributions from each component [19]. Aspen HYP can be made with different freeness and bulk, so its affect on strength properties may vary significantly, depending on the type and freeness of the kraft pulps blended. Further systematic study is, therefore, required.

Does substituting HYP for HBKP cause roughening during coating application and is more calendering needed to achieve the same gloss/smoothness target? — Coarse mechanical fibers in TMP or groundwood tend to roughen much more than those in chemical pulps when water is applied. However, since HYP is a chemically treated mechanical pulp, and

Properties	SBKP	HBKP	HYP
CSF (mL)	557	418	344
Baur-McNett R14 (%)	41.4	3.9	0.0
Baur-McNett 14/28 (%)	16.1	9.9	1.6
Baur-McNett 28/48 (%)	21.4	32.0	39.7
Baur-McNett 48/100 (%)	13.5	33.2	27.0
Baur-McNett P200 (%)	4.8	14.9	24.8
Kajaani fiber length—L. Wtd (mm, R48)	2.21	1.33	1.11
Kajaani coarseness (mg/m, R48)	0.153	0.121	0.155

I. The characteristics of HBKP, SBKP, and aspen HYP.

only a portion of kraft is substituted in wood-free basestock, its affect on surface roughening during coating application may be limited. If surface roughening does occur to some extent, the next question is whether more calendering is needed to achieve the same gloss or smoothness target.

Does substituting HYP for HBKP give poorer coating coverage and poor printability? — Coating coverage is very important for lightweight coating because the coat weight is not enough to completely cover the basestock surface. Poor coating coverage can lead to print nonuniformity. Basestock surface and structural properties, including initial roughness, compressibility, and surface roughening, all affect the coating coverage [20]. HYP substitution may affect all of those surface structure parameters, and therefore may affect coating coverage. The questions are whether the effects are negative or positive, and by how much.

To address those issues, we carried out a systematic investigation of the effects of substituting HYP for HBKP on the properties of basestock, coated, and calendered sheets. In this first report we focus on the mechanical properties of basestock used for lightweight coating.

EXPERIMENTAL

The softwood and hardwood bleached kraft pulps (SBKP and HBKP) used in this study were obtained from a northern U.S. mill; the aspen HYP was obtained from Tembec (grade 325/85 HW). SBKP is made of spruce while the HBKP here is a mixed bleached kraft pulp with 85% hardwood (aspen) and 15% softwood (pine). All three pulps were received in dry form. The two kraft pulps were refined to a freeness of 418 mL and 557 mL. Aspen HYP was used as received (no post-refining), with a freeness of 344 mL. The freeness of kraft pulps chosen here was based on the target used in a U.S. fine paper mill. The blends were made at different ratios:

- Softwood BKP was fixed at 50%
- Aspen HYP was varied from 0%, 10%, 15%, 20%, 25%, and 30%
- The balance of the furnish was made up with HBKP.

A dynamic sheet former (DSF; Noram, Pointe Claire, Quebec, Canada) was used for sheet forming. No retention aid was used. To simulate commercial LWC wood-free paper, a pulp consistency of 0.3% and a DSF wire speed of 1000 m/min were used. Sheets were pressed twice at pressures of 552 kPa (80 psi) and 690 kPa (100 psi), respectively. Sheets after pressing were then dried in a drum dryer at 150°C for 5 min. Grammage of the basestock was controlled at 41 g/m^2.

Properties	SBKP	HBKP	HYP
Moisture content (%)	7.7	7.9	9.4
Caliper (mm)	101	103	145
Bulk (cm^3/g)	1.71	1.75	2.42
Burst index (kP×m^2/g)	4.56	2.12	0.67
Tear index (mN×m^2/g)	13.69	8.15	2.28
Tensile index (N×m/g)	64.6	42.0	20.3
Breaking length (km)	6.58	4.28	2.07
Stretch (%)	3.27	1.98	0.80
TEA (mJ/g)	1447	587	91
Elastic modulus (km)	609	561	355
Zero-span tensile strength (km)	15.3	14.8	11.6
MIT double folds	257	9	too weak
Scott bond (J/m^2)	209	152	53
Light scattering coefficient (m^2/kg)	29.1	38.0	43.6
Brightness (%)	87.3	88.2	83.4
Opacity (ISO, %)	69.5	75.3	79.0

II. The properties of standard handsheets (60 g/m^2) made from HBKP, SBKP, and HYP (at the freeness listed in Table I).

Most of the mechanical properties of the basestocks were tested according to PAPTAC standard methods. All sheets from dynamic sheet former were tested along both machine direction (MD) and cross-machine direction (CD). Formation of the sheets was measured with an Ambertec instrument.

RESULTS AND DISCUSSION

Results in **Table I** show that aspen HYP has a much higher fines content than HBKP (24.8% vs 14.9%). As can be seen, the HYP fibers are slightly shorter, but coarser than HBKP (0.155 mg/m vs 0.121 mg/m).

Table II lists the properties of the standard handsheets made from HBKP, SBKP, and HYP. As expected, HYP has a much higher bulk than HBKP (2.42 cm^3/g vs. 1.75 cm^3/g), as well as a higher light-scattering coefficient and opacity. However, because of the much higher bulk, combined with its slightly shorter fiber length and lower fiber strength, HYP sheets have much lower strength properties than HBKP. The question then is whether the substitution of HBKP with HYP in a lightweight sheet would result in strength loss.

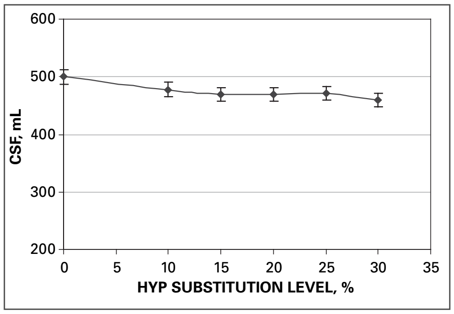
The properties of basestocks made with the dynamic sheet former at different levels of HYP substitution are discussed below. Note that the mechanical properties are the geometric mean of MD and CD.

Canadian Standard Freeness (CSF)

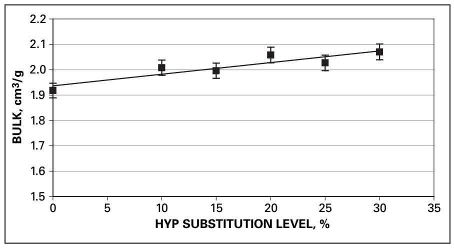
Figure 1 shows the effects of HYP substitution on the CSF of blended furnish. As can be seen, the substitution by HYP (up to 30%) slightly reduces the CSF of the blended furnish. Since the drainage is usually not an issue for lightweight sheet, HYP substitution is not expected to cause any drainage problem for paper machines.

Bulk

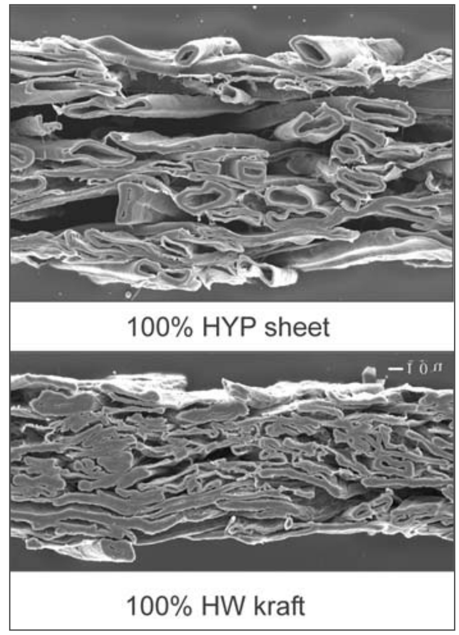
Bulk is very important for both mechanical properties and printability of various paper grades, particularly lightweight paper grades that require good bending stiffness. The main



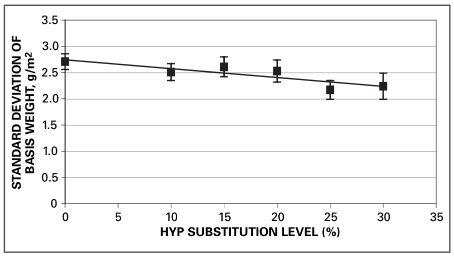
1. Effect of HYP substitution on CSF.



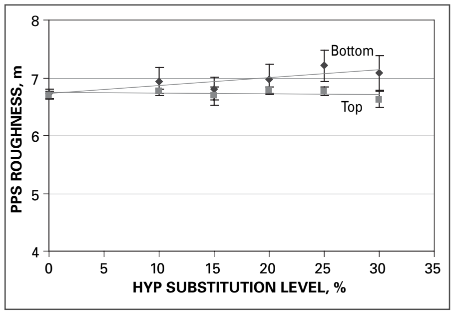
2. Effect of HYP substitution on bulk.



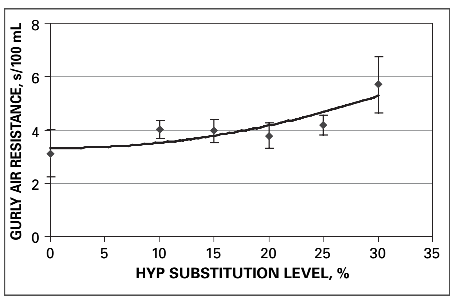
3. Cross-section images of typical HYP sheet and kraft sheet at 60 g/m².



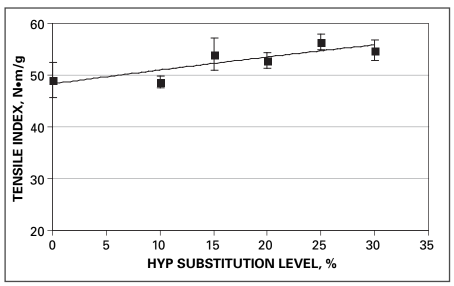
4. Effect of HYP substitution on basestock formation.



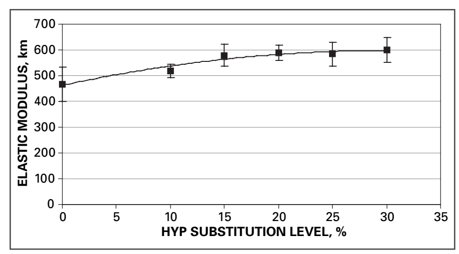
5. Effect of HYP substitution on PPS roughness.



6. Effect of HYP substitution on Gurley air resistance.



7. Effect of HYP substitution on tensile index.



8. Effect of HYP substitution on elastic modulus.

advantage of HYP is its high bulk created by the high fiber coarseness. Substituting HBPK with HYP results in some increase in bulk of the basestocks (**Fig. 2**). The higher the substitution level, the larger the increase in bulk. Correspondingly, sheet density is reduced with HYP substitution. The increased bulk can be attributed to the higher coarseness of the long fractions in HYP (Table I) and the lower collapsibility of HYP long fibers after the sheet is formed and dried, as shown by the SEM cross-section images (**Fig. 3**).

Formation

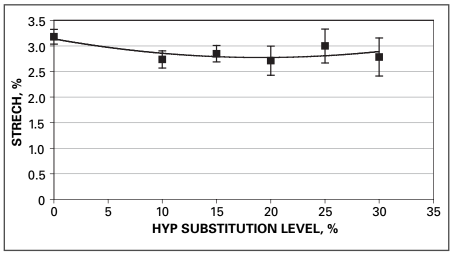
The formation, or basis weight variation, is measured by a β-radiation method and expressed as the standard deviation of basis weight (measured as point-to-point). **Figure 4** shows that the basis weight variation of the basestocks decreases slightly with the increase in HYP substitution, indicating an improved formation. The presence of fines and slightly shorter fibers in HYP is responsible for the improved formation. The improved formation should lead to better strength and structure uniformity of the basestocks.

Roughness

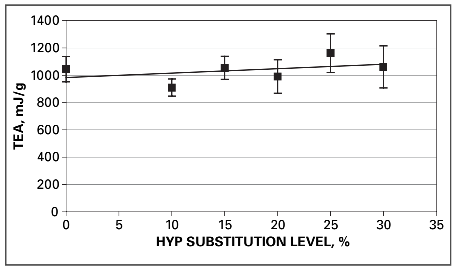
Good smoothness is important to achieve good coating coverage because low coat weight is applied to produce lightweight coated papers. Roughness here is measured by Parker Print-Surf (PPS) testing. **Figure 5** shows that PPS roughness of the top side is not affected by the HYP substitution. Although HYP is coarser and less collapsible than HBKP, it also contains more fines. The higher fines content compensates for the negative effects of the coarser and noncollapsible fibers. However, there is a slight increase in roughness on the bottom side. This may be caused by the lower fines content on the bottom side, resulting from poorer fines retention.

Air resistance

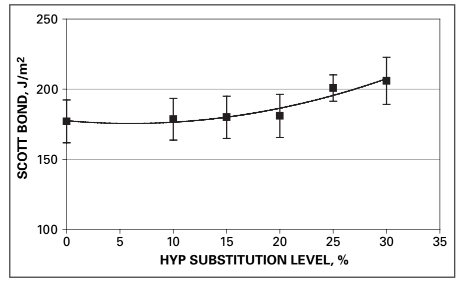
High air resistance (i.e., small pore size and high tortuosity) of the basestock is critical to achieve good coating holdout (i.e., less coating penetration). The air resistance is measured by the Gurley method. **Figure 6** shows that air resistance increases with the increasing level of HYP substitution. This is rather surprising because the HYP substitution increases bulk (Fig. 2). However, this can be explained by the higher fines content in HYP that helps reduce pore size and increase tortuosity [3]. In addition, slightly improved formation should also help the air resistance. This result indicates that HYP substitution could maintain coating holdout at a higher bulk.



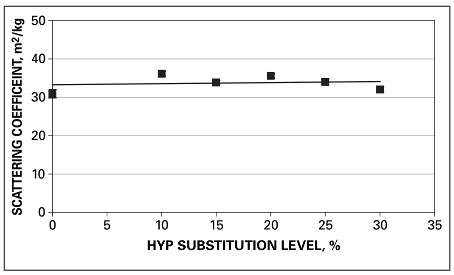
9. Effect of HYP substitution on stretch.



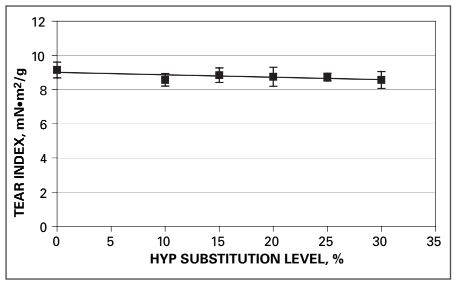
10. Effect of HYP substitution on TEA.



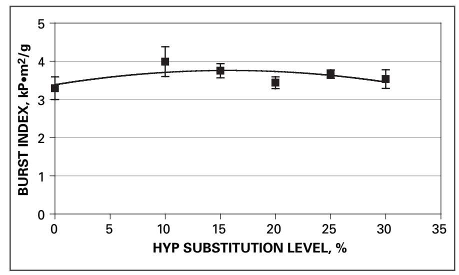
11. Effect of HYP substitution on Scott bond.



12. Effect of HYP substitution on light scattering coefficient (Note that error bar is too small to be seen).



13. Effect of HYP substitution on tear index.



14. Effect of HYP substitution on burst index.

Tensile properties

MD tensile properties (tensile strength and elastic stretch), instead of CD tear, are now considered to be the main factors controlling paper breaks in the pressroom [22]. **Figures 7** and **8** show the change in tensile index and elastic modulus with the HYP substitution level. Although HYP has much lower tensile strength than HBKP, we see no loss of tensile index and elastic modulus when HBKP is substituted with HYP. In fact, the tensile index and elastic modulus actually increase with HYP substitution. This clearly indicates a synergy between HYP and kraft pulps. Because HYP is actually a weaker fiber than HBKP (lower zero-span tensile strength; Table II), the increased tensile strength must come from the increased fiber-to-fiber bonding, as confirmed by the increase in elastic modulus.

The effect of HYP substitution level on the stretch is somewhat different. The stretch first decreases slightly with the substitution of 10% HYP, and then stabilizes with further increases in the HYP substitution level (**Fig. 9**). The initial decrease in stretch results because HYP has much lower stretch than HBKP (0.80% vs. 1.98%; Table II). However, the stretch also depends on the degree of bonding between fibers; better bonding allows greater use of the stretch potential of fibers. Therefore, the increased bonding with HYP substitution compensates for the effect of its low stretch potential of HYP, resulting in no significant change in stretch with increased HYP substitution levels up to 30%.

As a result of the increase in tensile strength and elastic modulus, but a slight decrease in stretch, the tensile energy of absorption (TEA) was almost constant with the increase in HYP substitution level (**Fig. 10**). The variations are within experimental error.

Although the bending stiffness (D) of the sheet was not measured in this study, it can be estimated from the elastic modulus (E) and sheet thickness (h) according to the following equation:

$$D = \frac{1}{12} \times E \times h^3 \quad (1)$$

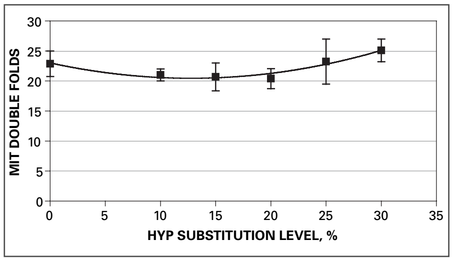
Therefore, the increased bulk, coupled with the increase in elastic modulus with HYP substitution, is expected to give a significant increase in bending stiffness. This shows that HYP substitution can be very beneficial to lightweight paper where bending stiffness is an important performance parameter.

Internal bond strength and light scattering coefficient

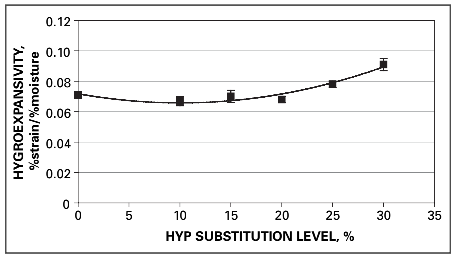
In the case of LWC wood-free papers, internal bond strength is very important for eliminating blistering and delamination in offset printing, while the light-scattering coefficient is important for opacity. **Figure 11** illustrates that Scott bond actually increases at the HYP substitution level above 20%. An increase of 10% in internal bonding at 20%-30% HYP substitution is important because delamination and blistering can be caused by poor internal bond strength of the basestock due to high-speed heatset offset printing. The increase in internal bond strength agrees well with higher tensile index and elastic modulus (observed in Figs. 7 and 8). The increase in internal bonding usually comes from increased bonded area, increased bond strength, or both. The data in **Fig. 12** show that the light scattering coefficient increases only slightly (mostly at low HYP substitution level). This indicates that the increase in internal bonding is due more to the increased bond area because highly fibrillated HYP does not scatter more light in this case.

Tear and burst index

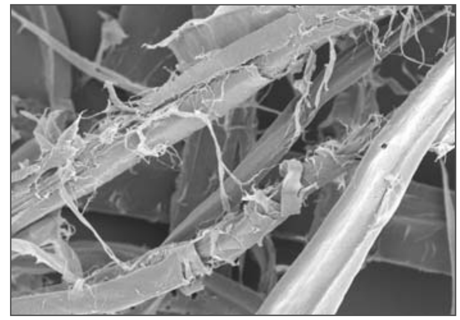
Figure 13 shows that although HYP has much lower tear index than HBKP (Table II), its substitution of HBKP (up to 30%) does not significantly affect the tear index of the lightweight basestock. This again indicates some synergy between HYP and kraft pulps. Although tear index is controlled mainly by fiber length, it is also affected by fiber bonding, particularly for shorter fibers. That is



15. Effect of HYP substitution on MIT double folds.



16. Effect of HYP substitution on hygroexpansivity.



17. The SEM images of typical HYP fibers.

why we see a constant tear index with increased HYP substitution. Although the average fiber length of the HYP is slightly lower than that of HBKP (Table I), the increased bonding helps maintain the tear strength.

Burst index is more or less unchanged with the increased HYP substitution levels (**Fig. 14**).

Folding endurance

Good fold strength is required for LWC wood-free papers to avoid fold cracking. The folding strength, as measured by MIT double folds, does not change significantly with the increase of HYP substitution level (**Fig. 15**). The variation is within experimental error. Note that MIT double folds inherently have large variation.

Dimensional stability

Dimensional instability (e.g., misregistration) is always an important issue in offset printing, particularly when mechanical pulps are used as part of the furnish. The hygroexpansivity (the ratio of percent strain to percent moisture content) is measured here as an indication of dimensional stability [23,24]. Hygroexpansivity is rather constant below 20% HYP substitution (**Fig. 16**). Above 20% HYP substitution, hygroexpansivity of the basestock increases. This result could be attributed to the increased bonding [23,24]. This result suggests that caution should be taken on dimensional stability when substituting HBKP with a large amount of HYP (e.g. >20%). However, it should be pointed out that the pulps used were in dry lap form, which is intrinsically more dimensionally stable. In addition, the degree of restraint in drying can have a significant effect on dimensional stability. Therefore, the dimensional stability of paper containing HYP made from an actual paper machine needs to be further examined.

Why substituting HYP for HBKP increase sheet strength

The results presented here are important, but rather surprising because the coarser fibers present in HYP are normally unfavorable for bonding. Three mechanisms may explain the observed increase in fiber bonding:

Fiber size distribution: Although HYP has an arithmetic average fiber length similar to that of HBKP (Table I), it has more fibers with shorter length (as indicated by the weight- and length-averaged fiber length. In addition, HYP has a much higher fines content than HBKP (24.8% vs. 14.9%). The short fibers and fines help form more "bridges" or "contacts" among the fibers (even among kraft fibers), and thus improve overall inter-fiber bonded area.

Highly fibrillated fiber surface: Figure 17 is a scanning electron microscopy (SEM) image of HYP fibers. As can be seen, due to the refining action, HYP has a highly fibrillated fiber surface. This helps increase fiber-to-fiber bonded area and bond strength (through interlocking), particularly between HYP and kraft fibers. This is supported by literature results claiming that the amount of fibrils is the most important parameter with regard to the bonding ability of fibers [21]. The fines in HYP and fibrils on HYP surface may act as anchor points to bond the kraft fibers.

Surface chemistry: Being a chemimechanical pulp, HYP has a higher hemicellulose content on the fiber surface than kraft fibers. The high hemicellulose content may also help improve bond strength.

More experimental work, however, is needed to have a better understanding of the precise mechanisms of the synergistic effects observed in this study. It should be pointed out that the synergistic effect of HYP substitution on strength properties depends on the freeness of HBKP. If the kraft pulps are refined to a freeness lower than that used in this study, HYP substitution might reduce the sheet strength.

CONCLUSIONS

Experimental results showed that although substitution of HBKP with HYP increased bulk, it had no negative effect on roughness and air resistance.

Substituting HYP for HBKP created synergy in strength properties of lightweight sheets (41 g/m^2). More specifically, HYP substitution up to 30% had a positive effect on tensile strength, elastic modulus, bending stiffness, and formation. Other properties, such as TEA, tear resistance, burst index, and folding endurance, were essentially not affected.

These results can be explained by fiber size distribution and the presence of large amount of fines, and by the well-developed fibrils on the surface of HYP fibers, which lead to increased bonding.

These results suggest that the substitution of hardwood kraft with aspen HYP up to 30% is technically feasible and even beneficial to produce a lightweight "wood-free" basestock.

The dimensional stability of paper containing HYP is not well resolved due to experimental limitations; further work is needed. **TJ**

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