Effect of HYP fibers on bulk and surface roughness of wood-free paper

YANG GAO, VIVEK RAJBHANDARI, KECHENG LI, YAJUN ZHOU, AND ZHIRUN YUAN

ABSTRACT: Two typical high-yield pulps (HYPs) used in wood-free paper grades, aspen HYP and birch HYP, were investigated for their effects on the bulk and surface roughness when substituting for hardwood kraft pulp in wood-free fine paper production. Results show that paper bulk, bending stiffness, and opacity can be improved significantly by both aspen and birch HYPs. Birch HYP has greater effects since birch fibers are larger and have higher coarseness. However, increasing HYP substitution rate increases paper surface roughness and decreases paper strength. Selection of HYP species and substitution rate should be made based on the needs of a specific paper grade.

Application: The results of the present investigation provide valuable information for the use of BCTMP in wood-free paper grades for improved paper bulk.

The bulk of paper has drawn increasing attention from both paper manufacturers and paper users in recent years. To a great extent, the bulk of paper determines the opacity and the stiffness of paper [1]. Modern photocopiers and printers demand high stiffness or caliper in order for paper to go through the machines smoothly. For papermakers, if higher bulk can be made, paper stiffness and opacity can be achieved by using less fiber material. That means producing the same caliper paper with reduced paper weight, saving raw material costs.

Several methods can be used to increase bulk in the paper manufacturing process. One of them is to add polymers to pulp furnishes. Ikeda et al. [2], and Kubota et al. [3] developed polymers, so-called the paper bulking promoter, which is basically a fatty acid polyamide that makes fiber surfaces hydrophobic. Asakura and Isogai [4] reported that in the case of the isostearic diamide salt, hydrophilic pulp fiber surfaces were covered in part with hydrophobic groups of the fatty acid diamide salts, whereas the stearic diamide salt molecules were presented as emulsion particles in the wet paper web without preventing the formation of internal bonds. This probably brought about the bulking effect by melting and partially spreading over the pulp fiber surface in the sheet during the drying process. The modification of fiber surfaces by bulking results in more porous and bulky paper sheets.

Some technological measures can also be taken in the papermaking process to increase the paper bulk, such as adjusting the temperature in drying or pressing processes, or lowering pressure in the press or calendering process. Rättö et al. [5] studied the effect of high-temperature and soft-nip calendering on the density of paper. They found that the line load had a dominant effect on the overall density of the calendered paper, whereas the temperature of the heated roll seemed to have a more pronounced effect on the density near the surface of the paper. Nygren et al. [6] investigated characteristics of mechanical and chemi-mechanical pulps, and indicated that the bulk would be quite different if the sheet was dried at different temperatures. The differences can perhaps be explained by the visco-elastic character of the fiber material, i.e., the lignin softening and lignin content in the pulp fibers for different pulps.

A cost-effective approach to improve paper bulk may be to use pulp fibers that have higher bulk, such as high-yield pulp (HYP) fibers. HYP, also known as bleached chemithermomechanical pulp (BCTMP), can now be made in tensile strength and brightness similar to that of bleached hardwood kraft pulp [7,8], while retaining some superior properties, such as high bulk, high opacity, and high fines content. Since most of the lignin remains in HYP, HYP fibers are stiff and do not collapse easily in the papermaking process [9]. Therefore, if HYP fibers are present in a papersheet, the stiff and uncollapsed fibers will contribute to the formation of a less dense sheet structure, thus improving the sheet bulk [7,8,10,11].

Aspen HYP and birch HYP are two typical HYPs that have been used in wood-free printing and writing paper grades to substitute for a portion of hardwood kraft pulp (HWKP) for improving the paper bulk [10-12]. By substituting aspen or birch HYP for a certain portion of HWKP, not only is the paper bulk improved, but also paper opacity and formation are improved. The fibers in HYP have much higher light scattering capacity, which contributes to the improved opacity of paper. In addition, the fines can fill in the voids formed by the long fibers and improve the formation of paper. The high specific surface area of fibers can also help retain more fillers in the paper sheet. Therefore, by substituting low-cost HYP for HWKP, not only is the paper quality improved, but also the production costs are reduced.

Pulp Sample	CSF (ml)	Fiber Length (mm)	Fiber Width (µm)	Coarseness (mg/m)	Fines P200 (%)	Bulk (cm^3/g)	Opacity (%, ISO)	Tensile (Nm/g)
Aspen HYP	478	0.642	24.6	0.160	23.1	2.46	82.1	14.35
Birch HYP	669	0.772	28.6	0.182	25.4	3.43	79.1	7.07
Spruce KP	483	1.942	-	0.149	9.7	1.43	64.1	80.15
Poplar KP	503	0.754	-	0.092	10.0	1.42	71.4	53.07

I. Fiber and handsheet properties of high yield pulp and kraft pulp.

However, if excessive HYP is used in paper, the surface smoothness will be negatively affected, which will affect the printing quality or the coating hold out when the paper is used as basestock for coating paper [8]. The objective of this paper is to investigate how the HYP addition rate will affect the bulk and surface smoothness of paper. Two typical HYPs used in wood-free paper are compared. Other paper properties including opacity, physical strength, and paper formation are also discussed.

EXPERIMENTAL

Pulp samples

Aspen and birch HYPs were provided by a commercial HYP producer. Spruce kraft pulp (KP) and aspen KP were also obtained from commercial production lines. Prior to mixing, spruce KP and aspen KP were refined with a PFI mill at 4,000 and 3,000 revolutions and to a CSF of 483 ml and 503 ml, respectively.

Handsheet properties

Handsheets with a basis weight of 60 g/m^2 (o.d.) were prepared according to TAPPI standard method T 205 om-88. The wood-free handsheets were made with 30% softwood KP and 70% hardwood KP, simulating the furnish composition of the typical wood-free fine paper grades. When substituting hardwood HYP for hardwood KP, 10%, 20%, and 30% of either aspen HYP or birch HYP were used to replace the same amount of hardwood KP in the furnish, keeping the rate proportion of softwood KP constant at 30%.

The tensile strength of the handsheet was tested with a Tensile Strength Tester by L&W. Roughness was measured with a Parker Print Surf Tester (with a standard measuring range of 0.6-6 µm). Stiffness was measured with a Taber 150-B Stiffness Tester. Opacity and brightness were measured with a TechniBrite Micro TB-1C Tester. Researchers made all measurements according to the relevant TAPPI standard methods. Paper formation was measured with a PaperPerFect Formation Tester (OpTest Equipment Inc., Canada).

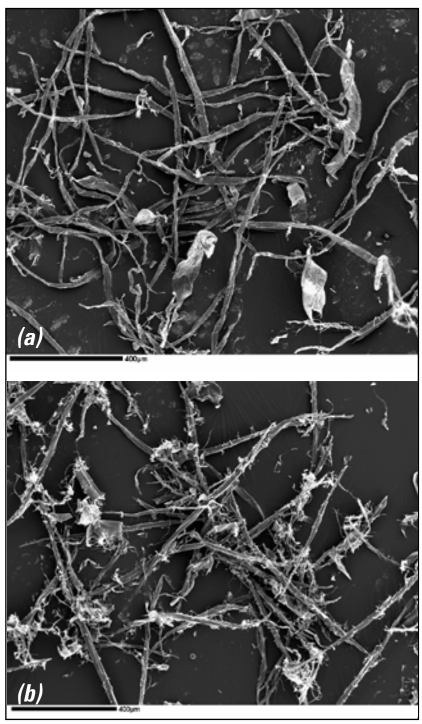
RESULTS AND DISCUSSION

Basic properties of HYP and KP

Table 1 compares the properties of individual fibers and pulp handsheets of HYPs and KPs. The length of the two HYP fibers is about the same as that of HWKP, but the fines content of HYPs is more than doubled. This will contribute to the improved formation and opacity in paper due to the small size and high specific surface area of the fines. The coarseness of aspen HYP (0.160 mg/m) and birch HYP (0.182 mg/m) is much larger than that of HWKP (0.092 mg/m), which is the major reason that HYP can be used to substitute for HWKP for improved bulk. However, the coarse fiber is also the cause for increased paper surface roughness.

It is also apparent that the physical strength and the bulk of the handsheets made from different pulps are significantly different. SWKP has the highest tensile strength, which is mainly attributed to its much higher fiber length, about 2 mm versus below 0.8 mm of hardwood pulps, and more flexible chemical pulp fibers; however, the more flexible fibers also result in denser paper sheets, thus, lower paper bulk. The bulk of both aspen HYP and birch HYP is much higher than of the two KP pulps. The bulk of birch (3.43 cm^3/g) is even higher than that of aspen HYP (2.46 cm^3/g). This is because of the larger fiber size, both length and width, and greater coarseness. It can be seen that even for the same hardwood HYP, different wood species can have significantly different properties. That is why paper manufacturers have to choose appropriate HYP type for their specific processes and products. In fact, even for the same wood species, HYP manufacturers can adjust their process technologies to make pulps with very different properties [7,8].

Figure 1 shows the SEM images of aspen HYP and KP fibers. It is apparent that hardwood KP has mainly long and



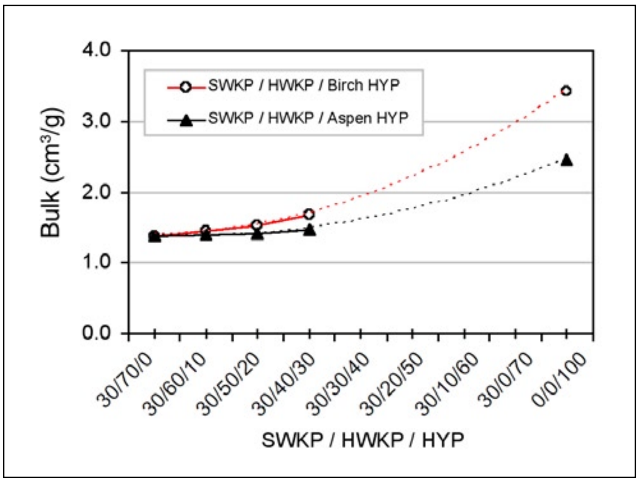
1. SEM images of fiber morphology of aspen kraft pulp fibers (a), and aspen HYP fibers (b).

flexible fibres which will form a compact network structure of paper. Hardwood HYP consists of long coarse fibers and a large portion of fines. When the HYPs are used to substitute for some hardwood KP, the fines will be good for formation and coarse, stiff fibers will make the paper structure bulkier; however, if the coarse fibers are present on the fiber surface, surface roughness will be increased.

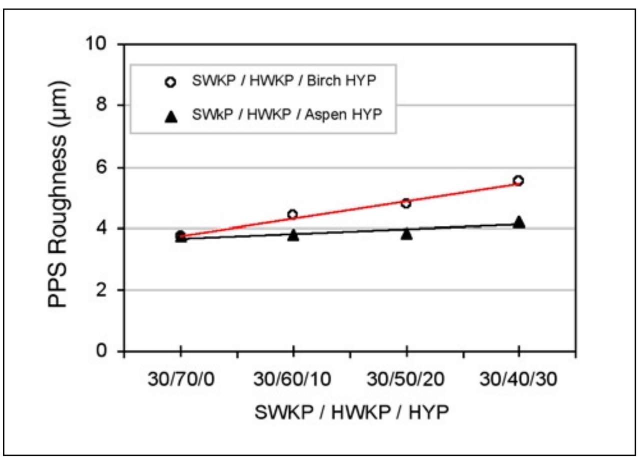
Bulk and surface roughness

In current wood-free paper production, most manufacturers use 5%-20% HYP in uncoated and use 5%-15% in coated paper. **Figure 2** shows that with increasing the HYP substitution rate, paper bulk increases; and at all substitution levels, from 10%-30%, birch HYP leads to higher bulk. This is expected since birch HYP fibers are larger and coarser than aspen HYP fibers.

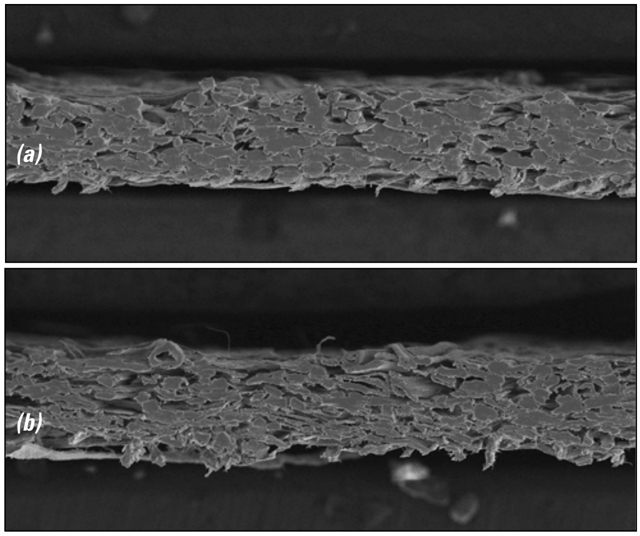
At a substitution level of 20%, the bulk of paper with aspen HYP and birch HYP increased by 10%, and 15%, respectively. In comparison with the pure HYP fibers as shown at 0% substitution, there is still a lot of room for improving the bulk by adding more HYP. However, this is limited by other paper properties. As shown in **Fig. 3**, by increasing the substitution rate of HYP, paper surface roughness increases. At a birch HYP substitution rate of 30%, the surface roughness increases from 3.75 µm to 5.52 µm. It is interesting to note that the increase in surface roughness by aspen is very minor. The roughness remains almost unchanged up to 20% aspen HYP substitution rate. This is because aspen HYP fibers are shorter and the coarseness is not as high as that of birch HYP fibers. In addition, the fines content of aspen HYP is about 23% versus fines content 10% of aspen KP. Therefore, although the coarse aspen HYP negatively affects the surface roughness, the high fines content may compensate the effect to a certain extent.



2. Paper bulk change with increasing HYP substitution rate.



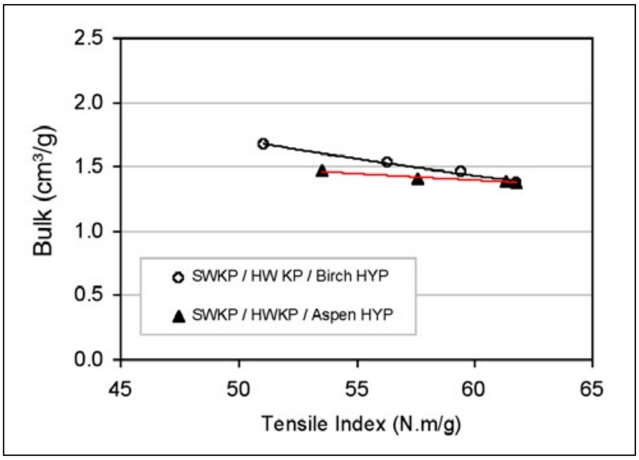
3. Paper roughness change with increasing HYP substitution rate.



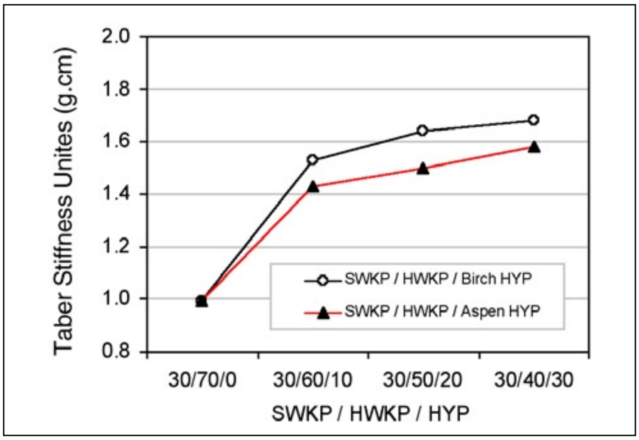
4. SEM cross-sectional views of the handsheet made from softwood and hardwood only (a), and KPs with 20% hardwood HYP (b).

The effect of HYP fibers on the bulk and surface roughness can also be observed from the cross section view of the handsheet containing HYP (**Fig. 4**). In the handsheet consisting of only KP fibers (Fig. 4a), the fibers are completely collapsed and no fiber lumen can be seen. Therefore, the sheet is more compact, which results in a lower bulk. The collapsed, flat fibers on the sheet surface forms a relatively smooth surface. In the handsheet containing HYP fibers (Fig. 4b), the HYP fibers are uncollapsed appearing tube-like, which leads to loose sheet structure, thus, a higher bulk. The uncollapsed tube-like HYP fibers near the surface lead to a relatively rougher sheet surface.

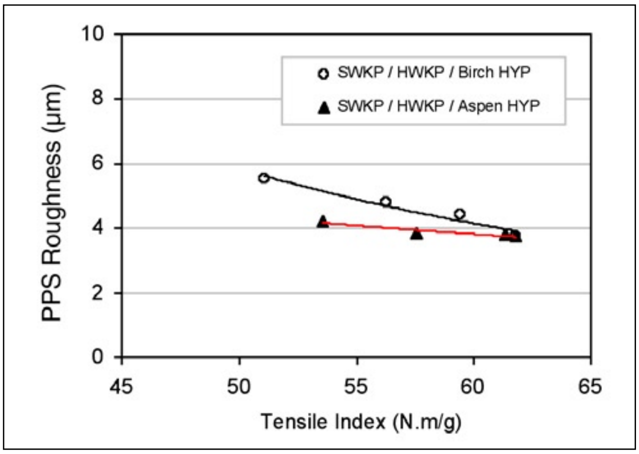
In order to further understand the effect of HYP and the substitution rate on the bulk and surface roughness, the paper bulk and PPS roughness are plotted against the tensile index as shown in **Fig. 5** and **Fig. 6**, respectively. It can be seen that bulk decreases with increasing tensile strength. It is understood that higher tensile means more flexible fibers or more bonded areas formed between fibers. Therefore, the sheet structure is more compact due to the increased bonding between fibers, resulting in a lower bulk. Similarly, if fibers bind together tightly, the fibers on the sheet surface will



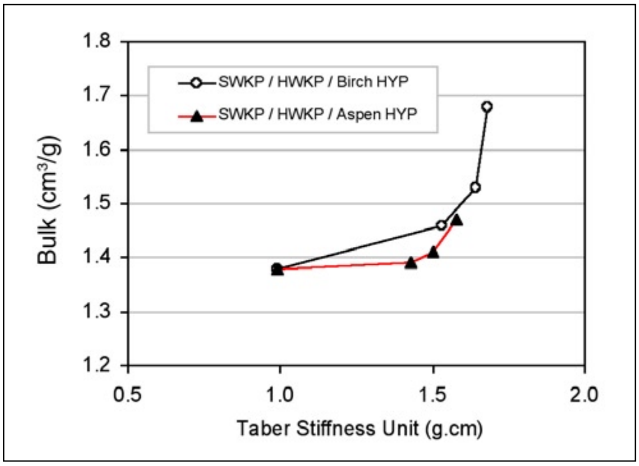
5 . *Bulk versus tensile strength.*



7. *Paper stiffness change with increasing HYP substitution rate.*



6. *PPS roughness versus tensile strength.*



8. *Paper stiffness versus paper bulk.*

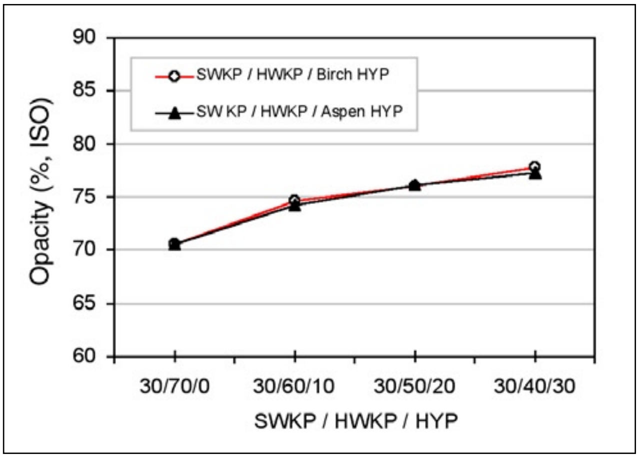
form a compact and relatively smooth surface. Therefore, the surface roughness decreases with tensile strength as shown in Fig. 6. Compared with aspen HYP, birch HYP fibers give higher bulk and lower surface roughness at the same tensile strength. This is mainly because birch fibers are larger and more coarse.

Bending stiffness

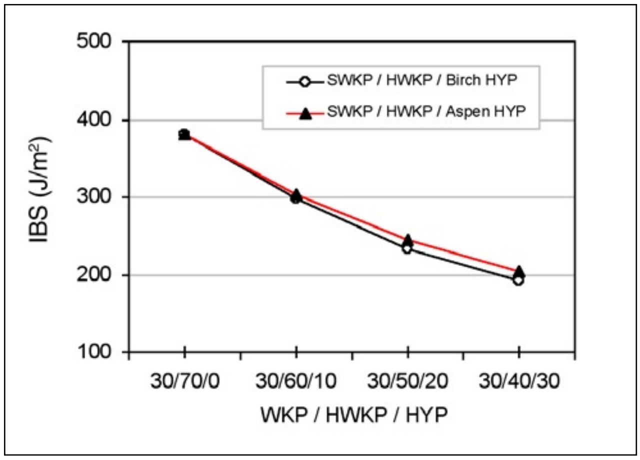
The bending stiffness is directly related to the performance of paper in printer and photocopier operation. The stiffer paper will go through the machines more easily, so fewer paper jams and less down-time are expected. **Figure 7** demonstrates that, by adding a small portion of HYP (10%), the bending stiffness increases substantially. The increase in stiffness at 10% substitution rate of birch HYP and aspen HYP is by 55% and 43%, respectively. Further increasing the HYP substitution rate increases stiffness gradually. It can be seen that the improvement rate by birch and aspen HYP is almost the same, which is a little bit different from the observation in bulk and surface roughness. **Figure 8** shows the relationship between bending stiffness and bulk. A small increase in bulk leads to a large increase in bending stiffness, in particular, in the low end of the bulk. This is expected since the bending stiffness is proportional to the third power of paper thickness or bulk. This observation shows that at the low HYP substitution level, even though the increase in bulk may not be significant (Fig. 2), the increase in bending stiffness can be large.

Opacity

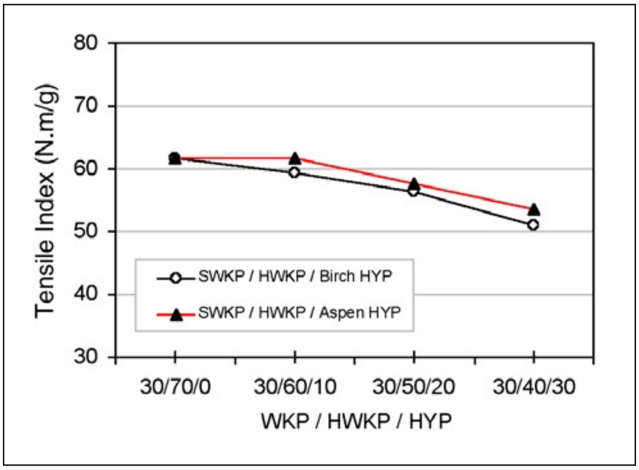
High opacity is another major advantage of HYP fibers, and one of the major objectives of using HYP to substitute for HW KP in wood-free paper grades is to improve paper opacity. It can be seen from Table 1 that both aspen and birch HYP have much higher opacity than SWKP and HWKP. Higher opacity will prevent print-through, especially when the basis weight is low. **Figure 9** shows that both aspen and birch can increase the paper opacity significantly. With a 10% substitution rate, opacity increases from about 70% to 74%, and with 30% substitution, opacity increases to about 79%. It can be seen that the effect of aspen and birch HYP on opacity improvement is almost the same. This is understandable since opacity is mainly determined by the high scattering capacity of fibers, and the fines in pulp are the major contributor to the high scattering capacity. Aspen and birch have almost



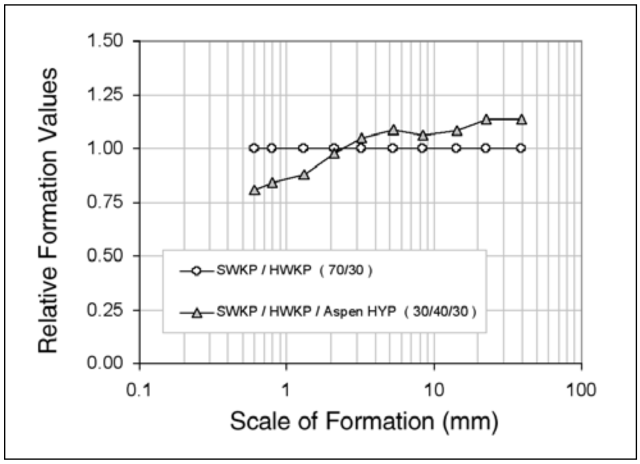
9. Paper opacity change with increasing HYP substitution rate.



11. Internal bond strength change with increasing HYP substitution rate.



10. Tensile strength change with increasing HYP substitution rate.



12. Paper formation (RFV) of handsheets containing aspen HYP.

the same amount of fines content (Table 1), so their contribution to opacity improvement is similar.

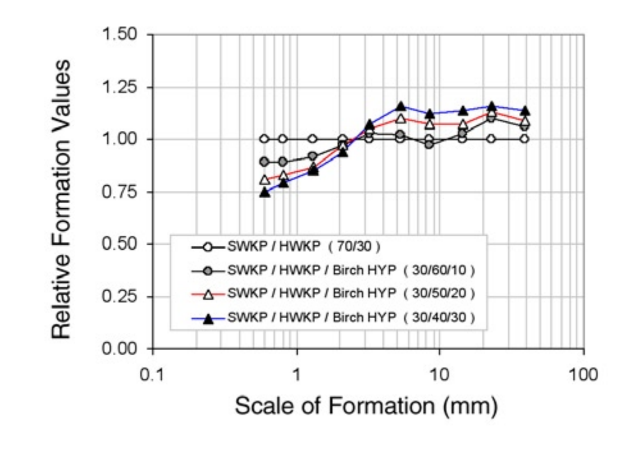
Strength properties

Figure 10 shows the tensile strength change with the increase in HYP substitution rate. At a low substitution rate (10%), the tensile strength is almost unchanged. At 30% substitution, the tensile strength decreases by only 10%-15%. Based on the tensile strength of HYP and KP as listed in Table 1, a much larger decrease by adding HYP may be expected. HYP fibers are coarser and stiffer, so the bounded area between fibers is smaller, which is already seen from the increased paper bulk as shown in Fig. 2. However, HYP has high fines content. Fines have much higher specific surface area which will enhance bonding between fibers. This will compensate for some of the negative effect on the strength by the coarse, stiff fibers. Some studies even observed increased paper strength by adding HYP, for a so-called synergy effect [12,13].

It can be seen from **Fig. 11** that the internal bond strength decreases substantially with increasing HYP substitution rate. At the 30% substitution rate, the internal bonding strength (IBS) decreases by about 50%. The effect of aspen and birch on the IBS is almost the same. Internal bond strength is determined by both the bonded area and strength of an individual bond. According to Li et al. [14], the surface of HYP fibers is partially covered by the lignin-rich middle lamella remainders. Lignin is more hydrophobic so will hinder the hydrogen bonding between fibers [15]. Therefore, increasing the HYP substitution rate, the IBS will continue to decrease. However, the tensile strength is determined not only by the IBS but also by fiber strength, fines, or the synergy effect. The decrease in tensile strength caused by the HYP substitution is not as significant.

Paper formation

The PaperPerFect Method (PPF) measures the uniformity of the mass distribution by classifying the formation into ten component ranges [16,17]. The important application of PPF is that certain formation components can be correlated to certain specific properties [16]. In theory, a relationship between the scale of formation and a specific paper property



13. Paper formation (RFV) of handsheets containing birch HYP.

can be established.

Substituting hardwood KP with hardwood HYP can improve the paper formation due to the high fines content of HYP. **Figure 12** shows the comparison of the relative formation value (RFV) of handsheet containing aspen HYP and containing only SWKP and HWKP as reference line at RFV 1.00. It can be seen that substituting 30% aspen HYP can improve the RFV significantly in the component range 2.6-60mm. This is expected since the fines of HYP can fill the voids and pores in the fiber network, which not only promotes inter-fiber bonding but also improves the paper formation.

It can also be seen from **Fig. 13** that birch HYP has a similar effect on paper RFVs. With increasing the substitution rate of birch HYP from 10% to 30%, the RFV continues to increase.

SUMMARY

Both aspen and birch HYP have greater fiber coarseness and more rigid fibers than the softwood and hardwood kraft pulp used in this study. By substituting either aspen or birch HYP for hardwood kraft pulp, paper bulk, paper opacity, and paper bending stiffness can be improved. In general, birch HYP gives a better effect than aspen HYP since birch HYP fibers are larger and have a higher coarseness than aspen HYP fibers.

However, by substituting HYP for hardwood kraft pulp, paper surface roughness increases. At a 30% substitution rate, surface roughness increases by 20% for both birch HYP and aspen HYP. The negative effect on surface roughness of aspen HYP is much smaller.

HYP fibers decrease the internal bond strength substantially due to the more rigid fibers and lignin-rich material on the fiber surface. However, the effect of HYP on the tensile strength of paper is not significant. This is due to the positive effect caused by the fines in HYP.

The results show that HYP of different wood species will have different fiber properties, and hence, have different effect on bulk and surface roughness when substituting for hardwood kraft pulp. Selection of HYP species and the substitution rate should be based on the specific paper grades and should strike a balance between bulk improvement and the tolerance for increased surface roughness. **TJ**

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INSIGHTS FROM THE AUTHORS

One of the most difficult things about this work was measuring the extreme roughness of the paper sheet from 100% high yield pulps. We needed to use different heads on the PPS (Parker Print Surf Tester). We feel that mills can use the results of this work to strike a balance between bulk and surface smoothness, based on their specific products. We would like to continue our research by investigating how different wood species would affect the use of HYPs.

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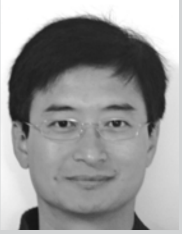

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