Improved High-Yield Pulp Network and Paper Sheet Properties by the Addition of Fines

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High-yield pulps (HYP, including BCTMP and APMP) have been increasingly used in various paper grades due to their unique properties. However, higher bulk at a fixed tensile strength is desirable for most HYP applications. This study explored the possibility of changing the bulk-tensile relationship of an aspen PRC-APMP pulp by adding fines from a well-refined HYP into a high freeness HYP (backbone pulp). The effect of backbone pulp freeness on the property-freeness relationship of the fines-reinforced pulps was also examined. The results indicate that to reach a target freeness, adding fines from a well-refined pulp (refined by a PFI mill at 20,000 revolutions) to a high-freeness pulp can help achieve a higher bulk and light scattering while maintaining a similar tensile strength, which is desirable in most of the HYP applications. To reach the same tensile index at a range of 20 to 24 Nm/g, the bulk of APMP550-fines (produced by fines and a pulp at 550 mL freeness) was 12 to 17% higher than that of the control pulp. The higher the freeness of the backbone pulp, the higher was the bulk and light scattering coefficient of fines-reinforced pulp when the fines-reinforced pulps were compared at the same freeness.

Keywords: High-yield pulp (HYP); Fines; Bulk; Tensile strength; Reinforced pulp

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INTRODUCTION

Among the various properties of high-yield pulp (HYP), bulk and strength are usually the most important from the perspective of end users (Zhang *et al*. 2011; Xu and Zhou 2007). To a great extent, the bulk of paper determines the opacity and the stiffness of paper. Modern photocopiers and printers demand high stiffness or caliper for paper to go through the machines smoothly. For papermaking, paper stiffness and opacity can be achieved by using bulky fiber material at a lower basis weight, resulting in savings in furnish costs (Gao *et al*. 2008).

HYP's network is typically weaker than that of chemical pulps; therefore, many previous studies have focused on improving the strength properties of HYP. HYP strength properties can be improved by optimizing chemical impregnation, applying more refining energy in the refining process, and by using higher sodium hydroxide dosage in the bleaching process. However, all these methods will decrease the pulp's bulk, which is not desirable for paper products that require high bulk (Zhang *et al*. 2011; Liu *et al*. 2011; Resalati 2007; Xu and Zhou 2007). For a given pulp, it is known that strength and bulk tend to be inversely proportional to each other, *i.e.*, a higher bulk typically leads to a lower strength. The question is whether the relationship between bulk and strength can be altered by adding some other material into a given pulp, with the objective of improving HYP strength without sacrificing bulk or improving bulk without decreasing strength.

The success of mechanical pulps as an important furnish component of a wide variety of printing and writing papers is largely dependent on their unique properties. The mechanical defibration process produces a large amount of fine material, and these fines play a significant role in development of both the optical and strength properties of mechanical pulps (Luukko and Paulapupo 1999; Sirviö and Nurminen 2004). Fines are defined as the part of a fiber suspension that passes a 200-mesh screen. Mechanical pulp fines improve paper strength by forming interfiber bonds because the capillary forces drawing fibers to fibrils are an order of magnitude higher than the corresponding forces drawing fibers to each other during papermaking (Campbell 1959; Silveira *et al*. 1996; Sundberg *et al*. 2003). Depending on the size and type of fines, fines can fulfill several structural functions. They can act as small fibers that can fill interstices and bridge gaps in the long fiber structure, and on occasion they may directly assist in forming a bond between two fibers (Retulainen *et al*. 2002; Silveira *et al*. 1996).

Recently, Zhang *et al*. (2012) used a small amount of bleached wheat straw pulp (BWSP) to improve HYP sheet/network properties. They found that with the addition of 5 to 10% well-refined BWSP, the HYP tensile strength could be increased by about 10 to 20% without sacrificing bulk. This was attributed to the microscopic fines present in a suspension of well-refined BWSP; such fines can act as binders to improve inter-fiber bonding within the HYP sheet or network. However, BWSP is not readily available to most of the papermakers in the world, and there are other issues related to using BWSP, such as low bulk, low opacity, and poor drainage due to its high parenchyma cell content, which are detrimental to the operation of a paper machine and/or to the paper qualities of many end-uses (Zhang *et al*. 2012; Cheng and Bi 2002).

The fines of BWSP have been shown to improve HYP's network characteristics, and HYP's fines can improve handsheets' strength properties (Zhang *et al*. 2012; Sundberg *et al*. 2003); however the effect of well-refined HYP fines on the HYP's network properties have not been fully demonstrated. Therefore, the objective of this study was to explore the potential of using well-refined HYP fines as a way to improve HYP strength without sacrificing bulk or to improve bulk without sacrificing strength, that is, to explore the possibility of changing the bulk-tensile relationship of HYP by adding fines from well-refined pulps to a high freeness pulp.

EXPERIMENTAL

Raw Materials

The hardwood HYP (P-RC APMP, made from aspen) with a freeness of 550 mL was from a paper mill in Henan province in China. It was obtained after typical two-stage high consistency refining and chemical treatment (NaOH 3%, H_2O_2 4.5%, Na_2SiO_4 3%, $MgSO_4$ 0.2%, and DTPA 0.2%). This pulp was also refined using a PFI mill (Model DCS-041PT KUMAGAT RIKI KOGY), at a refining consistency of 10% and a refining gap of 0.2 mm, at two different refining conditions (refining revolutions) to freenesses of 450 and 350 mL, respectively. These three pulps were referred to as the backbone pulps and named APMP550, APMP450, and APMP350, respectively. The properties of these three pulps are listed in Table 1.

Table 1. Properties of Aspen P-RC APMP Pulp at Three Different Freenesses

	APMP550 pulp	APMP450 pulp	APMP350 pulp
Number of refining revolutions (rev)	0	2500	5500
CSF (mL)	550	450	350
Bulk (cm^3/g)	4.10	3.76	3.08
Tensile index (N.m/g)	11.6	14.0	16.2
Internal bond strength (J/m^2)	26	31	44
Light scattering coefficient (m^2/kg)	55.1	54.9	54.5
Light absorption coefficient (%)	1.06	1.10	1.23
PPS roughness(μm)	7.42	6.80	6.37
B-M P16/R30 (%)	0.80	0.45	0.25
B-M P30/R50 (%)	21.20	12.90	10.10
B-M P50/R100 (%)	35.55	38.68	36.75
B-M P100/R200 (%)	15.75	20.13	23.90
B-M P200 (%)	26.70	27.83	29.00
FQA weight average length(mm)	0.524	0.497	0.445

Methodology

In the first step, the original pulp of 550 mL freeness was refined to 60 mL CSF (refining by the PFI mill at 20,000 rev.). The fines were collected and separated from the pulp of 60 mL freeness using a SWECO VIBRO-ENERGY Separator (LS18S33, USA) at 1.5% consistency and 200 mesh screen size. The morphological properties of fines are shown in Fig. 1.

In the second step, the obtained fines were added to the three backbone pulps as shown in Table 2, to produce fines-enhanced pulps (reinforced pulps) at different freenesses. These pulps were named APMP550-fines, APMP450-fines, and APMP350-fines, respectively. The effect of fines addition on pulp properties was then evaluated at the same freeness, when these pulps were compared to the control pulp that was made by refining the original pulp (APMP550) with the PFI mill to different freeness levels of 100- to 470-mL within the range of 2,000 to 15,000 refining revolutions, as shown in Table 2.

Also, the long fibers (B-M R50) from APMP550 and fines were mixed to further evaluate the effect of long fibers on pulp properties. Standard handsheets were made with white water recirculation to retain fines. The handsheet testing was performed according to various TAPPI standard methods. The fiber size distribution of all the pulps was classified according to Bauer-McNett (Model P4010.4 from Austria), and the fiber length was measured with a Fiber Quality Analyzer (FQA, Model LDA96 from Canada). An optical surface microscope (Model MMDICH-30 from Japan) was used to characterize the morphological properties of fines, and a scanning electron microscope (SEM, Model VEGA-TS5136 from the Czech Republic) was used to generate high-magnification surface and cross-section images.

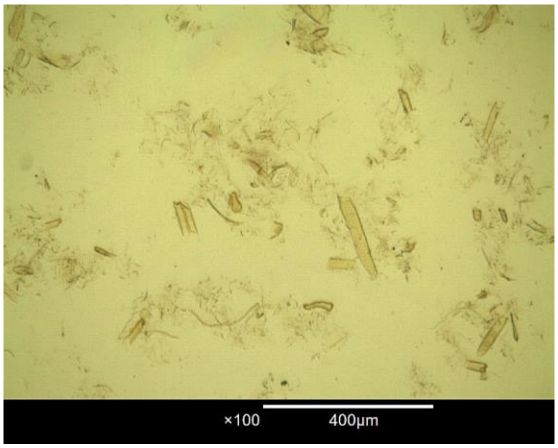

Fig. 1. Morphology of fines from pulp at 60-mL CSF

Table 2. Quantities of Added Fines Added to Three Backbone Pulps and the Freeness of Control Pulp

Pulps	APMP550-fines		APMP450-fines		APMP350-fines	
	APMP550 pulp (%)	Fines (%)	APMP450 pulp (%)	Fines (%)	APMP350 pulp (%)	Fines (%)
Reinforced pulps	95	5	95	5	95	5
	90	10	90	10	90	10
	85	15	85	15	85	15
	80	20	80	20	80	20
	75	25	-	-	-	-
Control pulps	Refining pulp at 550-ml CSF to the following freeness: 550-,470-,450-,400-,370-,350-,330-,220-,130-,100-mL					

RESULTS AND DISCUSSION

Effect of Freeness of Backbone Pulp on Properties of Reinforced Pulp

As stated in the Introduction section, the objective of this study was to examine the possibility of producing a pulp with a different bulk-tensile relationship as compared to refining the whole pulp to the target freeness. It is well known that mechanical pulp fines, especially fines separated from well-refined mechanical pulps, can decrease pulp freeness significantly. Therefore, the proposed approach is to add fines to a high-freeness backbone pulp to obtain the target freeness or strength.

First, the effect of freeness of backbone pulp on the properties of the new fines-reinforced (APMP550-fines, APMP450-fines, and APMP350-fines) pulps was examined at the same freeness. As expected, Fig. 2 shows that the addition of fines to the backbone pulp reduced pulp bulk, which is in agreement with a study by Zhang *et al*. (2011). However, it is noted that at the same freeness of fines-reinforced pulp, higher backbone pulp freeness leads to higher bulk for the fines-reinforced pulp, which is desirable for HYP. For instance, when the freeness of reinforced pulps was 250-mL, the APMP550-fines condition yielded higher bulk than APMP450-fines. The largest difference was observed between APMP550-fines and APMP350-fines. This could be mainly explained by the fact that for the three fines-reinforced pulps shown in Table 3, the higher the backbone pulp freeness, the more long fibers (B-M P30/R50) the fines-reinforced pulp mixture has. For example, in Table 3, which lists the Bauer-McNett fiber size distribution and the amount of fines added to reach a similar freeness of 210- to 225-mL, the APMP550-fines had a long fiber content of 13.72% *versus* 8% in the APMP350-fines. These long fibers tend to have less fibrillation and therefore low collapsibility due to a lower refining energy (Table 1) at a higher freeness (Lu *et al*. 2007; Gao *et al*. 2008). This contributes to the higher bulk of the reinforced pulp, which comes from a pulp that has higher backbone freeness. When the long fiber is further developed at the higher refining levels, the sheet will be closed up with the better conformability and console-dation of the fiber, which was also found by Corson *et al*. (2004) when they studied the effect of long fiber refining energy on the structure of handsheets of same freeness pulp by adding fines (composite of 2 parts primary fines *vs.* 1 part secondary fines) into long fiber at different refining energy levels. Table 3 also shows that a higher freeness backbone pulp required more fines addition to reach the same freeness.

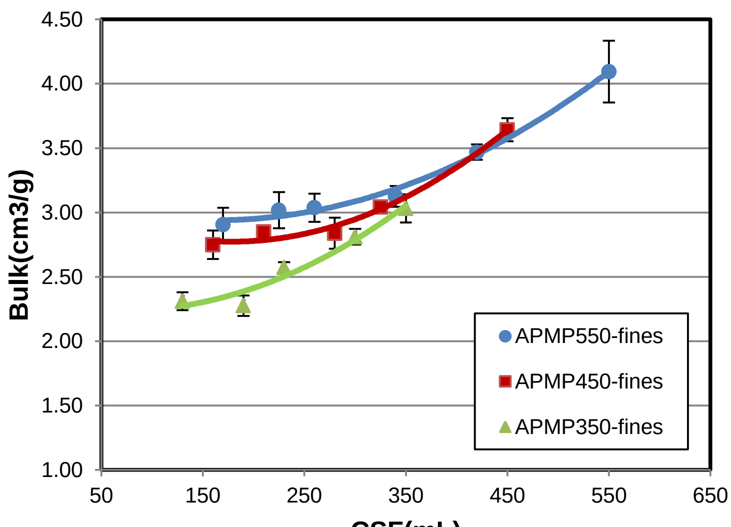

Fig. 2. Effect of freeness of backbone pulp on bulk of reinforced pulps

Figure 3 shows that similar tensile indices were obtained for these three reinforced pulps. Compared to low freeness backbone pulp, high freeness backbone has a lower strength property. However, high freeness backbone pulp needs more fines to achieve a given freeness in comparison of low freeness backbone pulp.

Table 3. Bauer-McNett Fiber Size Distribution and the Amount of Fines Required to Reach a Similar Freeness of 210 to 225 mL for Three Fine-Reinforced Pulps

Pulps	CSF (mL)	Total P30/R50 (%)	Total P50/100 (%)	Total P100/R200 (%)	Total fines (P200) (%)	Fines in backbone pulp (%)	Added fines (P200) (%)
APMP550-fines	225	13.72	30.82	15.39	39.77	19.77	20
APMP450-fines	210	10.99	32.66	17.82	38.27	23.27	15
APMP350-fines	230	7.95	33.24	20.63	37.87	27.87	10

The extra fines reinforce the network structure and lead to a similar tensile strength at a given freeness (Fig. 3). Meanwhile, since fines possess a large specific surface compared to fibers, they therefore contribute to the increase in light scattering coefficient. The higher the backbone pulp bulk, the higher the pulp light scattering coefficient (Fig. 4). For surface roughness of the handsheets, a similar trend and values are observed for APMP450-fines and APMP550-fines (Fig. 5). Although APMP350-fines had the lowest PPS roughness, the difference from that of the other two pulps was small. This is because the long fibers in high freeness backbone pulp are coarser and less collapsible fibers than those in low freeness backbone pulp. Such fibers are the main cause of roughening because of their poor bonding ability (Hu *et al*. 2006).

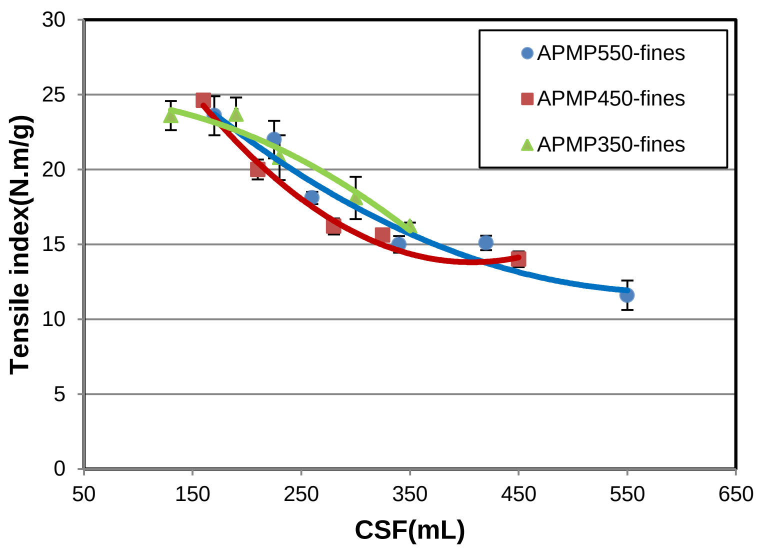

Fig. 3. Effect of freeness of backbone pulp on tensile index of reinforced pulps

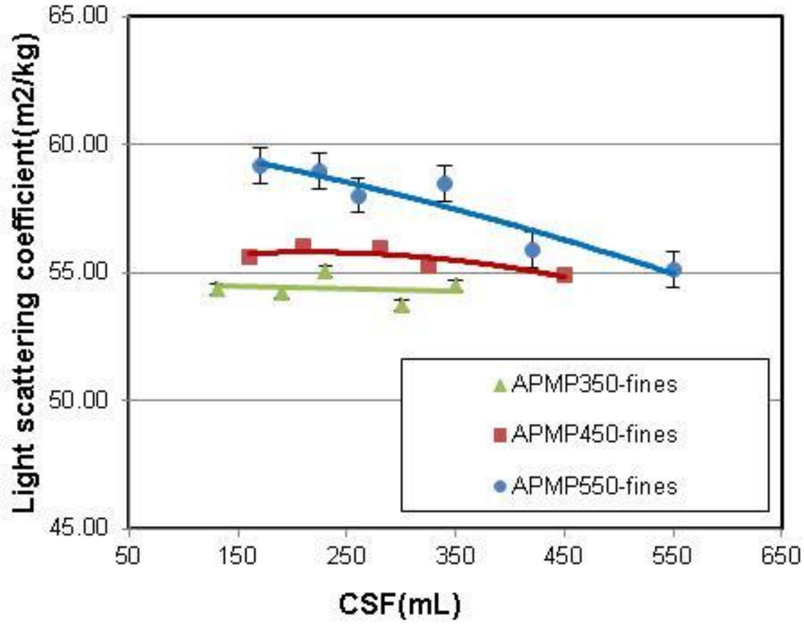

Fig. 4. Effect of freeness of backbone pulp on light scattering coefficient of reinforced pulps

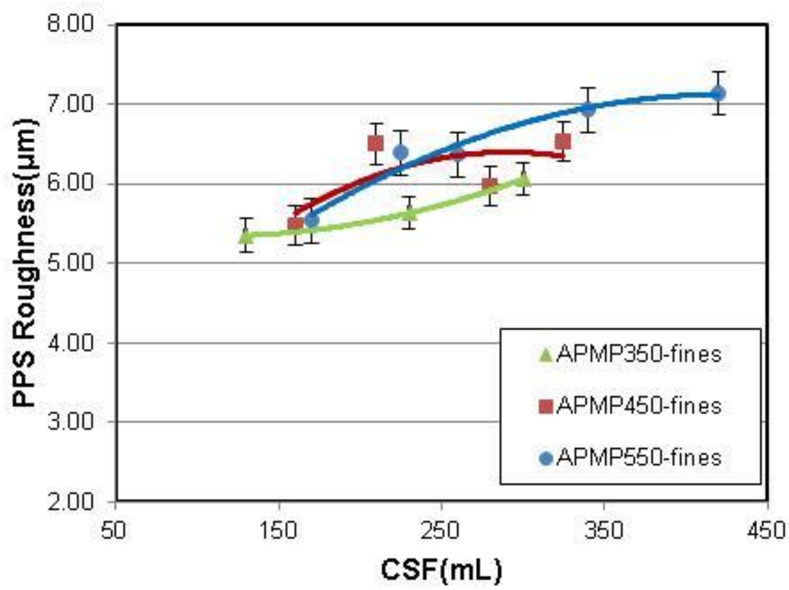

Fig. 5. Effect of freeness of backbone pulp on PPS roughness of reinforced pulps

The results shown in Figs. 2 through 5 indicate that to reach a target freeness, adding fines from a well-refined pulp can help achieve a higher bulk and light scattering while maintaining a similar tensile index. This is desirable in most HYP applications. Because the APMP550-fines condition yielded the highest bulk and light scattering at the same freeness, in the discussion below, this pulp was used to compare with the control pulp, which is refined by PFI to the same freeness levels (whole pulp refining).

Comparison between the Reinforced Pulp and the Control Pulp

Figure 6 and 7 shows that at the same freeness, adding fines to the backbone pulp led to a higher pulp bulk, while maintaining a similar tensile index when compared to the control. However, the difference in bulk was only observed at a low freeness range of 170 to 350 mL. For example, at the freeness level of 170 mL, the bulk of APMP550-fines was about 17% higher than that of the control (2.91cm^3/g *vs.*2.46 cm^3/g). Why did the difference only occur in the low freeness range? Figure 8 shows that at the same freeness, the APMP550-fines condition had more long fibers as well as more fines than the control. The difference in long fiber content was larger at the low freeness range, as was the fines content. Also, the difference in long fiber content was larger than that in fines content. It appears that for these two pulps, bulk is mainly determined by the long fiber content, while fines and the middle fraction contribute mainly to tensile strength. This is further supported by Table 4, which shows that increasing the concentration of long fibers in the pulp led to a higher bulk. The long fibers fraction (B-M R50) was separated from the APMP550 using Bauer-McNett classification. Table 3 also shows that at the same fines addition, the bulk of (long fibers+fines) was consistently higher than (APMP550+fines), indicating that long fibers contributed more to handsheet bulk than the middle fractions of the pulp.

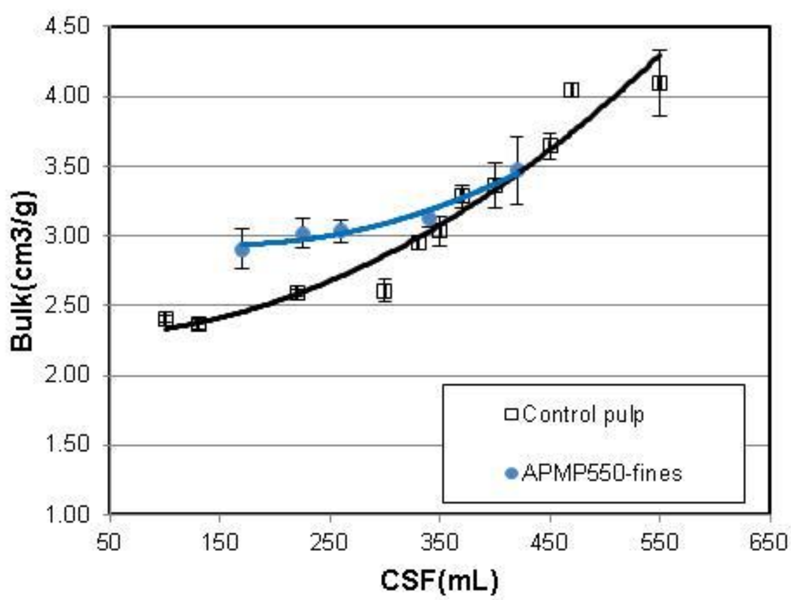

Fig. 6. Bulk-freeness relationships of APMP550-fines and control

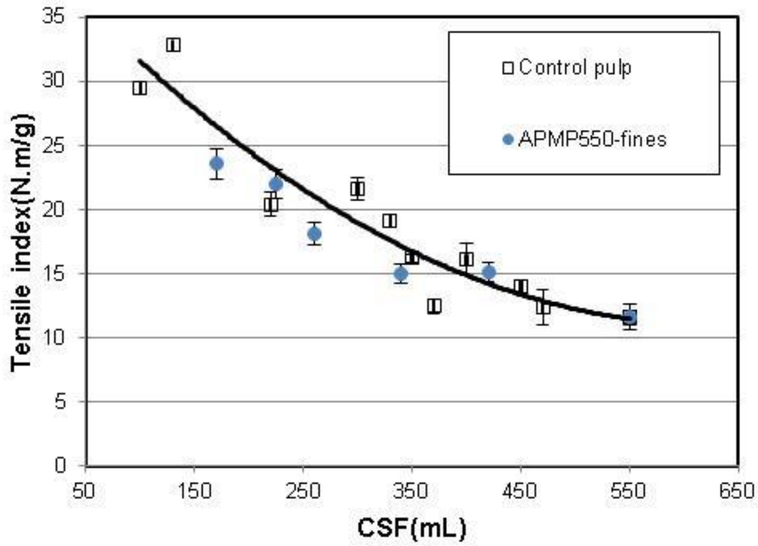

Fig. 7. Tensile-freeness relationship of APMP550-fines and control

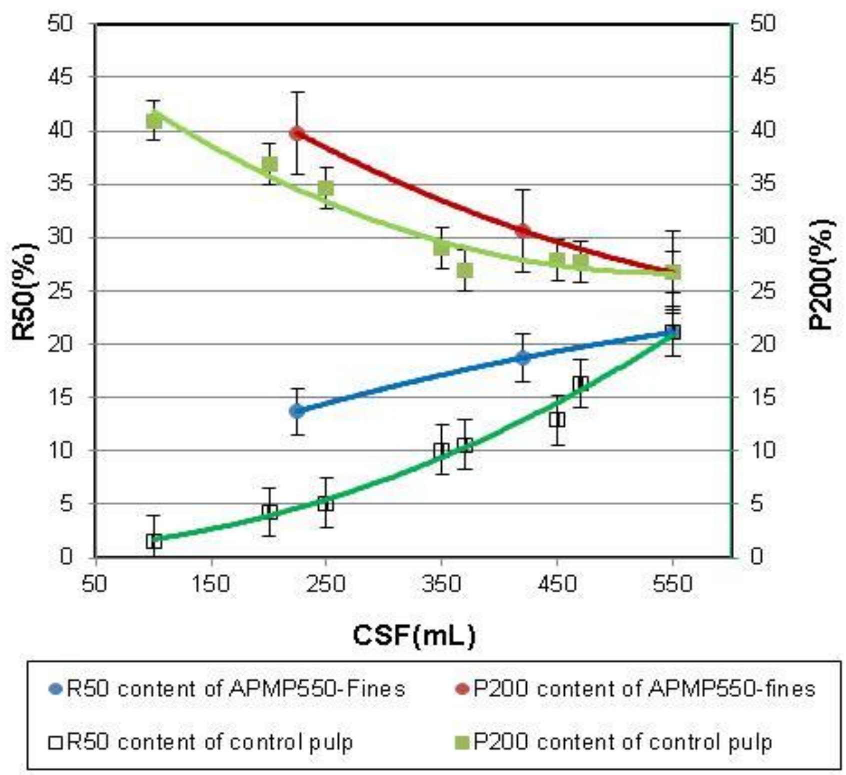

Fig. 8. Long fiber content (B-M R50) and fines content (B-M P200) of APMP550-fines and control

Table 4. Effect of Long Fibers and Fines on Handsheet Bulk

Fines addition (%)	Percentage of Long fibers or APMP 550 pulp (%)	Handsheet bulk(cm^3/g)	
		Long fiber+fines	APMP550-fines
0	100	4.164	4.095
5	95	3.918	3.469
10	90	3.574	3.125
15	85	3.571	3.037
20	80	3.415	3.018
25	75	3.038	2.907

Figure 9 plots the bulk-tensile relationship, which is very important for many HYP applications. A higher bulk at a given tensile index is desirable in applications such as board, printing papers, and writing papers. Figure 9 shows that adding fines from well-refined pulps to a high freeness pulp changes the bulk-tensile relationship at a high tensile range when compared to the control. For example, in the tensile index range of 20 to 24 Nm/g, the bulk of APMP550-fines is 12 to 17% higher than the control. This high tensile range corresponds to the low freeness range in Fig. 2.

One hypothesis is that the fines separated from the well-refined HYP (at 60-mL freeness) have many fibrils and micro-fibers, as Fig. 1 shows. Such fibrillar fines can be absorbed onto HYP fibers, thus increasing both bonding area and bonding strength. That is, they act like "binders" between HYP long fibers without changing the "rigidity/ collapsibility" of the long fiber network that contributes to pulp bulk. Such a relationship was also reported by Zhang *et al*. (2011) when they added well-refined bleached wheat straw pulp to an aspen HYP. Also as Fig. 10 shows, the fines filled the micro-voids in a reinforced pulp network. Such an effect was also shown by Kamaludin *et al*. (2011) for the EFB (oil-palm empty fruit bunch) APMP pulp network.

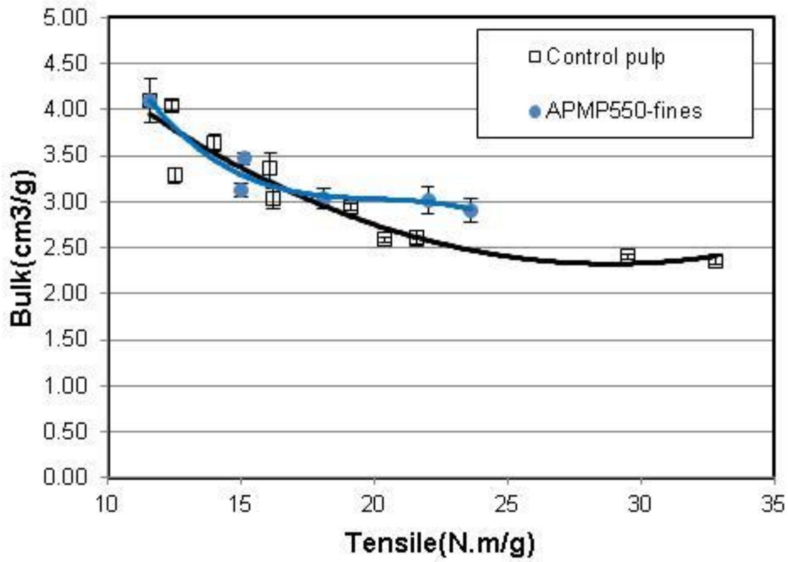

Fig. 9. Relationship of bulk and tensile index of APMP550-fines and control

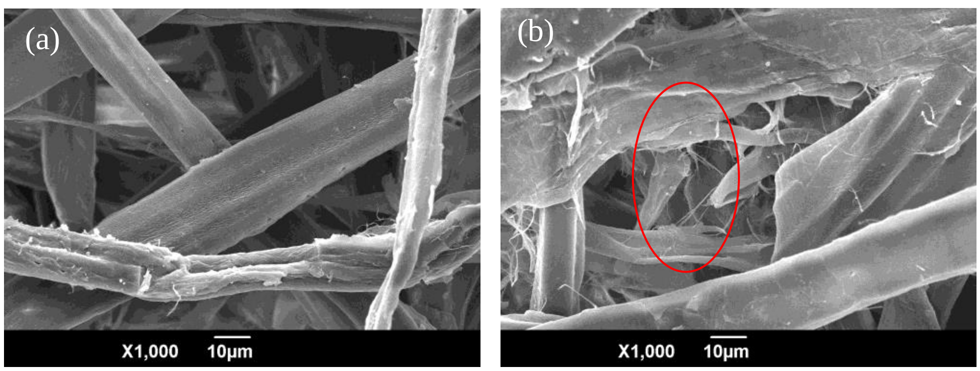

Fig. 10. SEM images of the reinforced pulp network: (a) HYP long fiber network without fines; (b) HYP network with 80%long fiber pulp and 20% fines

Figure 11 shows that APMP550-fines has a higher light scattering coefficient than the control, especially at a low freeness range. This could be explained by the fact that the APMP550-fines condition had more fines (Fig. 8) and a higher bulk than the control at the same freeness (Fig. 6). Figure 12 shows that APMP550-fines had a slightly rougher surface than the control, most likely due to the higher long fiber content in the former. On the other hand, the difference in roughness was marginal because the APMP550-fines condition also had a higher fines content than the control.

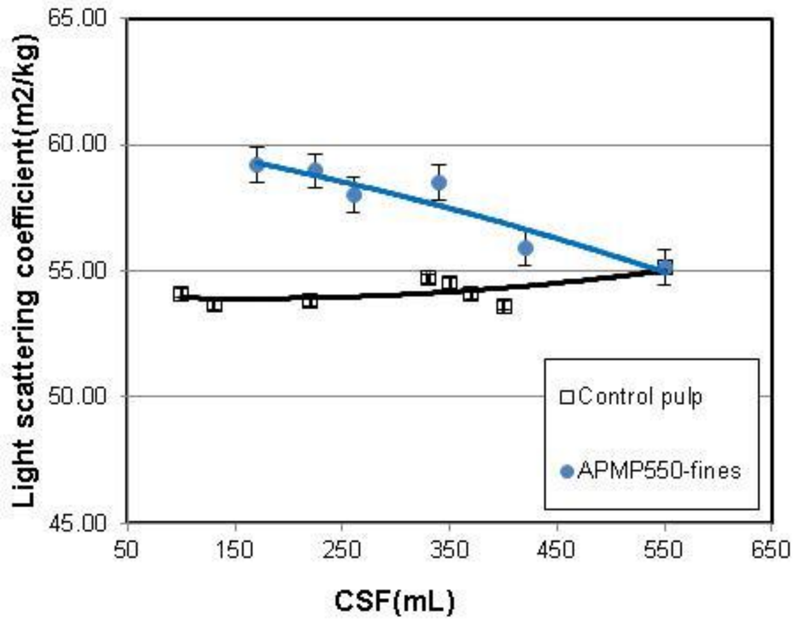

Fig. 11. Light scattering coefficient-freeness relationship of APMP550-fines and control

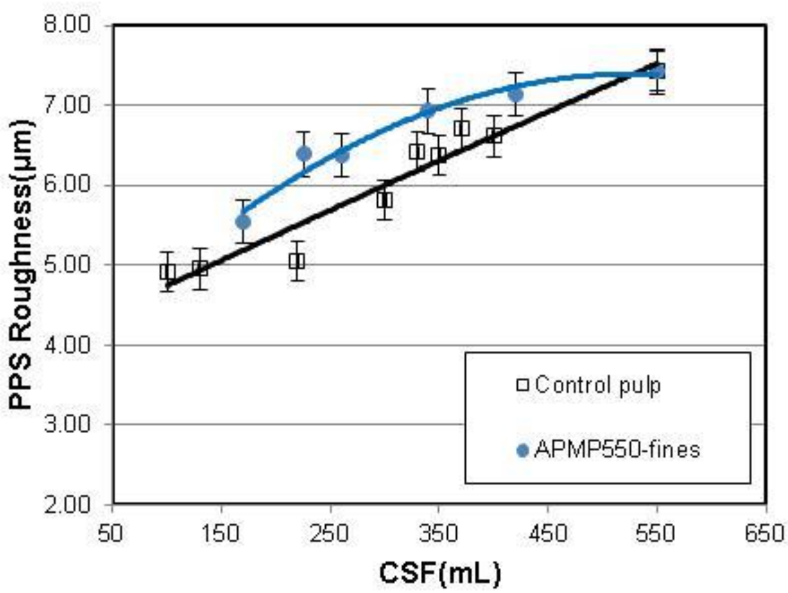

Fig. 12. PPS roughness-freeness relationship of APMP550-fines and control

CONCLUSIONS

1. This study explored the possibility of changing the bulk-tensile relationship of an aspen PRC-APMP pulp by adding fines from a well-refined pulp into a high freeness

backbone pulp. The effect of backbone pulp freeness on the property-freeness relationship of the fines-reinforced pulps was also examined.

2. The results indicate that to reach a target freeness, adding fines from a well-refined pulp to a high-freeness pulp can help achieve a higher bulk and light scattering while maintaining a similar tensile index, which is desirable in most HYP applications. To reach the same tensile index, the bulk of APMP550-fines was 12 to 17% higher than that of the control pulp at a tensile index range of 20 to 24 N.m/g. The higher the freeness of the backbone pulp was, the higher were the bulk and light scattering coefficient for the fines-reinforced pulp.

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