EFFECTS OF FURNISH AND REFINING ON PROPERTIES OF HOUSEHOLD PAPER

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This study examined the effects of furnish mixing ratios, fiber morphologies and pulp refining on the softness of household paper, based on laboratory experiments and actual production line results. The experimental results indicated that refining significantly reduced the softness of household paper. At a pulp freeness of < 500 mL CSF, the effect was alleviated. Hand-felt tissue softness results based on Tissue Softness Analyzer determinations and bulk softness changed according to the fiber length-to-thickness ratio of fiber morphological characteristics. The surface softness of tissues varied with the fiber slenderness ratio. On-site production can modulate the product softness to remain at higher levels by selecting fibers with a greater length-to-thickness ratio and fiber slenderness ratio, coupled with adjustments to the furnish mix and refining degree. At the same quality level, selecting suitable pulp was estimated to save US$ 6~10 pulp costs per ton of paper produced.

Keywords: softness, fiber morphology, refining, furnish mix, household paper

INTRODUCTION

A major characteristic of household paper (specifically, tissues) is softness. Factors affecting softness perceptions include the fiber type (*e.g.*, wood species), pulp type (*e.g.*, Kraft or mechanical), furnish mix, pulp refining, creping conditions, *etc.*[1-3] Softness is further classified into bulk softness, such as the cushioning effect, and surface softness, such as the hand-felt sensation by the fingertips.[4-6] There are three types of mechanical means of testing softness, *viz.*, the Handle-O-meter, Gramophone Stylus Analyzer and Tissue Softness Analyzer (TSA). The Handle-O-meter only measures the stiffness of the paper, where softness is the inverse of stiffness; the Gramophone Stylus Analyzer measures surface softness; while the TSA can simultaneously measure hand-felt softness (TSA HF), surface softness (TS 750) and bulk softness (TS 7). Major producers of world-wide household papers, however, often apply human tactile evaluation techniques and develop similar panel determinations of human softness evaluation methods, which are based on paired comparisons to differentiate deviations of test specimens from standard samples with a ranking of the softness accordingly.[6,7]

Fibers from different tree species differ morphologically, and this can be used in production. Characteristics such as the fiber length, coarseness, population distribution, length-to-thickness ratio (L/T), collapsibility, *etc.* are quantifiable parameters. Fiber length is affected by the tree species, mechanical treatments, growth conditions, part of the tree used, *etc.* Typical softwood fiber lengths are 1.8~2.5 mm, while those of hardwoods are 0.7~1.1 mm. Fiber coarseness is a product of the fiber cell wall thickness and fiber peripheral length, which represents the mass of per unit length, typically in mg/m or mg/km. Fiber coarseness is affected by the fiber width and cell wall thickness, with the former in typical softwoods being around 25~50 μm, the latter ranging between 3~8 μm, with a coarseness of 0.15~0.35 mg/m; typical hardwood fibers have widths of 10~35 μm, cell wall thicknesses of 2~5 μm, and fiber coarseness of 0.07~0.135 mg/m. The fiber population distribution is defined by the optical scattering area and hole-filling capacity; the values for typical softwood fibers are

$(1.0{\sim}2.5) \times 10^6$ fibers/g; while those for hardwood fibers are $(10.0{\sim}15.0) \times 10^6$ fibers/g.[8-10]

Despite numerous studies describing wood pulp fiber morphological characteristics of different species, those dealing with the effects of fiber morphology on household paper properties are limited. Kibblewhite[1] described how household paper softness is affected by fiber morphological parameters of perimeter (2 x (width + thickness)), wall area (proportional to the coarseness), width/thickness (proportional to collapsibility), and population (proportional to 1/(length x wall area)). However, he only described trends and did not provide concrete data support. Gigac and Fiserova[11] investigated the effects of refining conditions, such as the refiner tackle type and specific edge loading, and pulp types (spruce, birch and eucalyptus) on the properties of household papers, including the bulk softness, absorbency, tensile strength and wet tensile strength.

Kerekes and Schell[12] investigated the effects of fiber morphology on flocculation, using fiber length and coarseness as indicators. They found that longer fibers led to a decrease in uniformity by increasing the degree of fiber contact (crowding factor) and floc size. With increasing coarseness for the same fiber length, the crowding factor further diminished the uniformity. Mixtures of long and short fibers of a given length-weighted average length gave the same non-uniformity as individual fractions of the same fiber length. El-Hosseiny and Anderson[13] studied the effects of fiber length and coarseness on the bursting strength of paper and found that an increasing fiber length enhanced the bursting strength. Conversely, increased fiber coarseness reduced the bursting strength. Perng and Wang[14] investigated pulp furnish and refining effects on the performance of greaseproof paper, in which long-fiber furnishes selected were northern softwoods and Radiata pine, and the short-fiber furnishes were eucalyptus, Indonesian hardwoods, acacia, *etc*. The results showed that more refining tended to produce a tighter-textured paper, which was more suitable for greaseproof purposes. The thick-walled mixed Indonesian hardwood pulp tended to produce handsheets with the most open structure, hence the highest air permeability and the least Kit values. Also, in 2009, Perng *et al*.[15] studied the effects of five fiber morphologies (two long fibers and three short fibers) and refining on handsheet properties of the bulk, water absorption, air permeability, and dry and wet opacities. Fiber morphological indicators were the fiber length, coarseness and population. Their experiments on individual pulp fibers indicated that, along with increasing degrees of refining, the fiber population increased proportionally, pulp freeness and fiber lengths changed in an inverse manner, while fiber coarseness irregularly changed. Blended furnishes, on the other hand, indicated that along with increases in hardwood pulp proportions, the freeness, fiber length and coarseness changed with an inverse trend, whereas the fiber population also increased. Thus, it is feasible to use refining and blending of softwood and hardwood pulps to adjust the stock to meet the required freeness and fiber morphological properties for paper machines.

The main objective of this study was to understand the effects of furnish, fiber morphology and pulp refining on the softness of household papers, so as to provide a reference for furnish selection, increase product quality (specific softness) and reduce costs. The parameters of softness we considered were TSA HF, TS7, TS750, and panel softness units (psu). This study was carried out in two phases. In the first phase, household paper furnish typically used in Taiwan, which includes softwood pulp mixed with three different hardwood pulps, was PFI-refined and handsheets were formed to examine their tensile and bursting strengths and softness, as well as to understand the effects of furnish and refining on household paper properties. In the second phase, based on the handsheet results, the optimal fiber morphologic types were selected to provide the furnish mix and form “super-soft” household paper using an on-site paper machine, so as to verify the effect of fiber morphology of the furnish on the softness of the commercial product.

EXPERIMENTAL

As mentioned above, the experiments were conducted in two phases. In the first phase, laboratory studies based on household paper furnish typically used in Taiwan, which included one softwood fiber and three hardwood fiber blending options, were carried out. The effects of fiber morphology and degree of refining on the household paper properties were studied. In the second phase, the laboratory handsheet results were used to select optimal fiber types to blend for long- and short-fiber furnish mixes, and we conducted on-site forming with a paper machine to produce "super-soft" tissues and verify the effects of fiber morphology on tissue softness.

In the experiments, fiber properties were measured as follows: pulp freeness was tested according to TAPPI T227 om-99, using a CSF apparatus made by Lesson (New Taipei city, Taiwan); while fiber length, coarseness and population distribution were tested according to TAPPI T234 cm-84 using Kajaani FS-200.

Household paper property tests included the following:

- Grammage: in accordance with TAPPI T410 om-98;
- Thickness: according to TAPPI T411 om-97, and bulk was derived from these;
- Tensile strength: according to TAPPI T576 pm-07, using a Thwing-Albert instrument;
- Bursting strength: according to TAPPI 403 om-10, using model 0168 from Lesson;
- Water absorbency: according to ISO 8787, capillary rise of water, by the Klemm method, using a model 0301 tester from Lesson;
- Softness: handsheet softness was determined using a TSA by Emtec (Leipzig, Germany).

Hand-felt softness (TSA HF), bulk softness (TS 7) and surface softness (TS 750) were determined. The German company Emtec has developed in recent years a commercial household paper TSA. Test results are reputed to correlate at ≥95% with human hand-felt softness. For this, TSA HF is provided with an internal function, which is obtained by synthesizing parameters of TS 7, TS 750, grammage, thickness, number of plies, *etc*. TS 7 represents the bulk softness of the specimen and is determined by the noise in decibels emanating from the specimen, a greater number of decibels representing coarser and harder fibers. TS 750 represents the surface softness for which the surface coarseness is measured, and the coarser the surface the less soft it is.[16] The hand-felt softness of commercial tissue products was obtained by a panel test commonly used for household papers, in which panelists felt the paper by hand and ranked the softness. Ten panelists carried out paired comparisons of test specimens to a standard, and 60 sets of data were used to produce psu data.

Four experimental fiber types were used: bleached Kraft northern pine pulp (long-fiber, Prince George Mill, Canfor, Canada), bleached Kraft Asian eucalyptus pulp (short-fiber, Chung Hwa, Hwa-lien, Taiwan), bleached Kraft South American eucalyptus (short-fiber, Arauco, Santiago, Chile), and bleached Kraft acacia pulp (short-fiber, PT TeL, Kalimantan, Indonesia).

Laboratory pulp refining mimics the on-site furnishing principle of a household paper mill, and a PFI refiner (in accordance with TAPPI T248 cm-00; Model 2510, KRK, Saitama, Japan) was used to refine the pulp mix. Blends of softwood pulp with the three different hardwood pulps were disintegrated in a standard disintegrator (in accordance with TAPPI T205 sp-02; using a model-100 disintegrator, from Lesson), and then were refined with a PFI refiner. By controlling the number of revolutions, the mixed pulps were beaten from the original freeness to 550, 450 and 350 mL CSF, respectively. Handsheets were prepared according to TAPPI T205 sp-95, and handsheets of 30 gsm grammage were formed (to simulate typical household paper grammage). After air-drying overnight, the handsheets were conditioned in a constant temperature and humidity room for at least 3 h. Then, household paper properties of tensile strength, bursting strength and softness were measured. Each experimental set was replicated three times to provide a standard deviation (SD). The total number of experimental sets was 16, and 48 experiments were consequentially conducted.

In the second phase, in order to further examine the effects of the furnish mix on the softness of household paper, we proceeded with on-site machine forming of products to increase the household paper softness and reduce production costs. Based on indications of the first-phase experiments, we selected South American eucalyptus pulp (ES) to substitute for Asian eucalyptus (EA) and acacia (A), which are currently used in the mill. The actual furnish mixes are listed below:

- Control: northern pine pulp 25% + acacia 55% + Asian eucalyptus 15% + broke 5%;
- Experimental set 1: northern pine 20% + South American eucalyptus 75% + broke 5%;
- Experimental set 2: northern pine 15% + South American eucalyptus 80% + broke 5%;
- Experimental set 3: northern pine 10% + South American eucalyptus 85% + broke 5%.

Upon disintegration, the pulps were refined with a double-disk refiner (DDR) in the continuous mode until the desired freeness was reached, before proceeding with machine forming. A crescent-former tissue machine of a Taiwan paper mill was deployed. The machine was purchased in 1988, with a width of 2400 mm, and speed of 1600 m/min. The base sheets produced were converted using constant-pressure embossing to produce and package the commercial tissue product. We then obtained a representative sample from the lot and proceeded with physical property tests for tensile strength, water absorbency, bulk and hand-felt softness.

RESULTS AND DISCUSSION

Fiber morphology

Morphological features of the four wood pulps used in the study are described in Table 1. Northern pine fiber had an average length of 2.51 mm, a fiber length-to-thickness ratio (L/T) of 697, a coarseness of 0.165 mg/m, a fiber slenderness ratio (L/W) of 14.8, and a population of 2.0×10^6 fibers/g. Among hardwood pulps, the ranking of fiber lengths was as follows: South American eucalyptus (0.76 mm) > Asian eucalyptus (0.70 mm) > acacia (0.61 mm); the ranking of the fiber length-to-thickness ratios (L/T) was the following: acacia (311) > South American eucalyptus (298) > Asian eucalyptus (259); the coarseness ranking was: Asian eucalyptus (0.078 mg/m) > South American eucalyptus (0.070 mg/m) > acacia (0.059 mg/m); fiber slenderness ratio was in the order of South American eucalyptus (10.9) > acacia (10.3) > Asian eucalyptus (8.97); and the population was sequentially acacia (33.3 10^6 fibers/g) > Asian eucalyptus (26.9 10^6 fibers/g) > South American eucalyptus (22.4 10^6 fibers/g).

Table 1
Fiber morphological features of the experimental softwood and hardwood pulps

Pulp type	Long-fiber	Short-fiber		
	Northern softwood BKP	Acacia BKP	Asian eucalyptus BKP	South American eucalyptus BKP
Symbol	N	A	EA	ES
Freeness (mL, CSF)	713	598	612	625
Fiber length (L) (mm) (LWAL)	2.44	0.61	0.70	0.76
Cell wall thickness (T) (μm)	3.50	1.96	2.70	2.55
L/T	697	311	259	298
Coarseness (W) (mg/m)	0.165	0.059	0.078	0.070
L/W (fiber slenderness)	14.8	10.3	8.97	10.9
Population (10^6 fibers/g)	2.0	33.3	26.9	22.4

LWAL, length-weighted average length; BKP, bleached kraft pulp

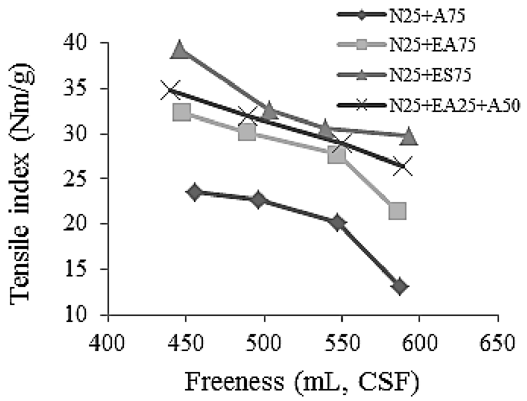

Figure 1: Effects of pulp freeness and furnish mix on the tensile index of resulting handsheets; N, northern pine; EA, Asian eucalyptus; ES, South American eucalyptus; A, acacia

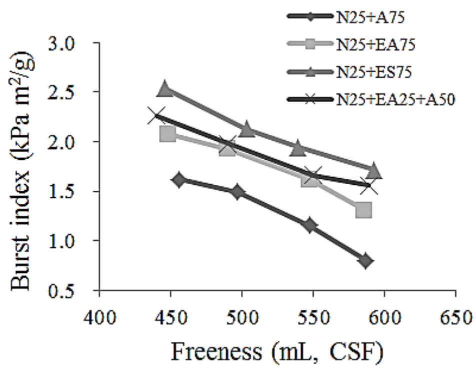

Figure 2: Effects of pulp freeness and furnish mix on the burst index of resulting handsheets; N, northern pine; EA, Asian eucalyptus; ES, South American eucalyptus; A, acacia

Effects of furnish and pulp freeness on household paper properties

In this part of the experiment, three hardwood pulps (75%) were individually blended with northern pine pulp (25%), and then refined to 600, 550, 500 and 450 mL CSF to examine the effects of the pulp blend and refining on the tensile and bursting strengths and softness of the resulting handsheets. An on-site blend of 25% northern pine, 25% Asian eucalyptus and 50% acacia pulp served as the control.

Tensile strength

The effects of the pulp freeness and furnish mix on the tensile strength of the handsheets are described in Figure 1. The pooled SD of tensile indices was 0.70 Nm/g, with 32 degrees of freedom. The figure shows that the tensile index increased with an increasing degree of refining (a decrease in freeness), and there was a positive correlation. The blend with acacia produced the lowest tensile strength, with Asian eucalyptus and

South American eucalyptus pulp strengths in an ascending order. Only the latter had a strength value greater than that of the control. This was probably due to South American eucalyptus pulp having a greater fiber length and slenderness ratio (L/W) than the other two pulps.

Bursting strength

The influence of the pulp freeness and furnish mix on the bursting strength of the handsheets is shown in Figure 2. The pooled SD of burst indices was 0.06 kPa m^2/g, with 32 degrees of freedom. Similar to the tensile index trend, the figure shows that the burst index increased with the degree of refining (a decrease in pulp freeness) and showed a positive correlation. The bursting strength of the acacia blend handsheets was the lowest, followed by Asian eucalyptus and South American eucalyptus in an ascending order. Only the South American eucalyptus blend handsheets exhibited a bursting strength greater than that of the control. The similarity of the burst index to the tensile index was probably due to the South American eucalyptus blend having a greater fiber length and slenderness ratio.

Softness

Handsheet softness was determined using an Emtec TSA instrument, and hand-felt softness (TSA HF), bulk softness (TS 7) and surface softness (TS 750) were determined, respectively.

The effects of the pulp freeness and furnish mix on the TSA HF are shown in Figure 3. The larger the value of the TSA HF was, the better the hand-felt softness was. The pooled SD of the TSA HF was 6.68%, with 32 degrees of freedom. The figure shows that refining significantly reduced the hand-felt softness. At <500 mL CSF, the effect was alleviated. The probable reason was that, at a pulp freeness of <500 mL CSF, the fibers had been heavily beaten, which caused them to bind tightly, which in turn affected the softness. Hence, practically, upon reaching the required tensile and bursting strengths, the production line should shun further refining. The results of the furnish mix indicated that the TSA HF values of the handsheets obtained were in the order of the blend containing acacia > South American eucalyptus blend > Asian eucalyptus blend > control. The hand-felt softness trend indicated that hand-felt softness was correlated with the fiber length-to-thickness ratio (L/T), and appeared to show no correlation with individual indicators of fiber length, coarseness or population.

Figure 4 shows the effects of the pulp freeness and furnish mix on the TS 7 bulk softness. A lower TS 7 value means better bulk softness. The pooled SD of TS 7 was 3.51 db, with 32 degrees of freedom. In the figure, refining obviously decreased the bulk softness of the handsheets; at a freeness of <500 mL CSF, the effect was lessened. The effects of the furnish mix were similar to those of hand-felt softness, with the acacia blend superior to the South American eucalyptus and Asian eucalyptus blends in a decreasing order. The bulk softness trend was like that of hand-felt softness, which was correlated with the fiber length-to-thickness ratio; whereas individual indicators of fiber length, coarseness or population were ineffective determinants of bulk softness.

Figure 5 shows the effects of the pulp freeness and furnish mix on the TS 750 or surface softness of the handsheets. The lower the value was, the greater the surface softness was. The pooled SD of TS 750 was 9.41 db, with 32 degrees of freedom. Among furnish mixes, the effect of refining on the surface softness was inconsistent and tended to reflect the combined influences of fiber morphology and refining. The surface softness performance of the handsheets indicated that the South American eucalyptus-containing blend led the pack, followed sequentially by the acacia, control and Asian eucalyptus groups. The trend of surface softness indicated that it was proportional to the fiber slenderness ratio (L/W), and was not effectively reflected by individual indicators of fiber length, coarseness or population.

On-site forming experiments

We further investigated the effects of the furnish mix on the softness of household paper, so as to increase the softness and reduce product costs of commercial products. The actual furnish mixes were as follows:

- Control: northern pine 25% + acacia 55% + Asian eucalyptus 15% + broke 5%;
- Experimental set 1: northern pine 20% + South American eucalyptus 75% + broke 5%;
- Experimental set 2: northern pine 15% + South American eucalyptus 80% + broke 5%;
- Experimental set 3: northern pine 10% + South American eucalyptus 85% + broke 5%.

Under the premise of maintaining tissue product quality performances (*i.e.*, the MD/CD tensile ratio, water absorbency, bulk and softness), because South American eucalyptus is intrinsically stronger than acacia and Asian eucalyptus, therefore, the production line suitably adjusted the production refining strategy to produce freeness values that ranged between 500~550 mL CSF.

After the production run, the base sheets were converted with fixed-pressure embossing, packaged and then sampled for tensile strength, water absorbency and bulk tests, in addition to the hand-felt softness determination. Hand-felt softness was evaluated by a panel test to analyze 60 sets of data, and results were given in panel softness units (psu).

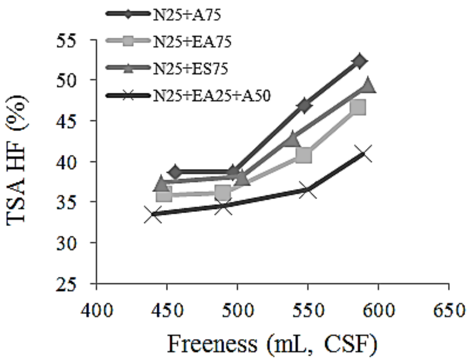

Figure 3: Effects of pulp freeness and furnish mix on the TSA HF softness of handsheets; N, northern pine; EA, Asian eucalyptus; ES, South America eucalyptus; A, acacia

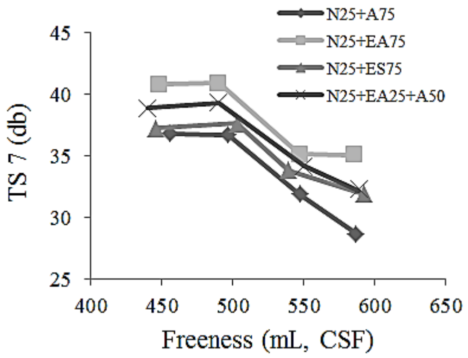

Figure 4: Effects of pulp freeness and furnish mix on the bulk softness (TS 7) of handsheets; N, northern pine; EA, Asian eucalyptus; ES, South American eucalyptus; A, acacia

Table 2
Results of the on-site production run based on furnish mixes

Blend ratio of the furnish mix (in %)	N25+A50+EA20+B5	N20+ES75+B5	N15+ES80+B5	N10+ES85+B5
Tensile strength (MD/CD) (g/25 mm-2 ply)	504/180	396/177	391/177	371/181
Tensile strength (MD/CD) ratio	2.8	2.2	2.2	2.0
Water absorbency (mm/min)	20.5	22.5	20.5	20.0
Bulk (μm/1 ply)	157	165	164	166
Hand-felt softness (psu)	2.2	3.0	3.0	2.3

N, northern pine; EA, Asian eucalyptus; ES, South American eucalyptus; A, acacia; B, broke; MD, machine direction; CD, cross direction

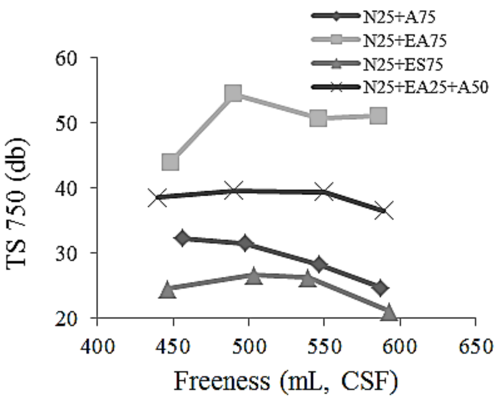

Figure 5: Effects of pulp freeness and furnish mix on the surface softness (TS 750) of handsheets; N, northern pine; EA, Asian eucalyptus; ES, South American eucalyptus; A, acacia

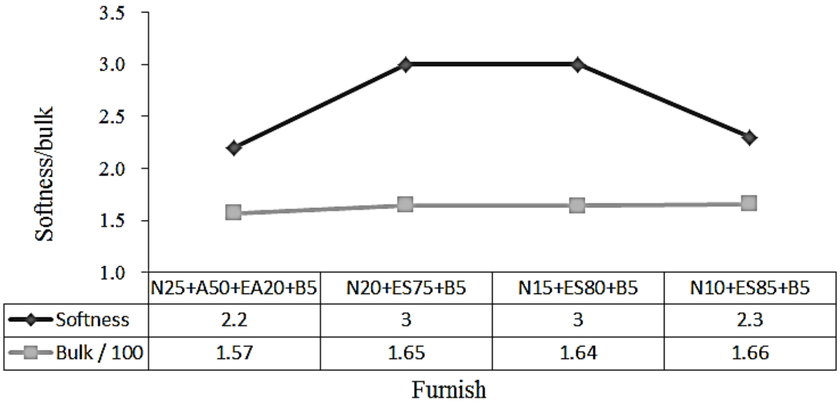

Figure 6: Effects of on-site experimental furnish mix on the softness and bulk of the products; N, northern pine; EA, Asian eucalyptus; ES, South American eucalyptus; A, acacia; B, broke

The effects of on-site furnish mixes on the physical properties and hand-felt softness are described in Table 2, and the on-site furnish mix effects on hand-felt softness and paper bulk are shown in Figure 6. The figure indicates that adding South American eucalyptus caused the base sheet hand-felt softness and bulk to significantly increase. Regardless of the blends of long-fiber northern pine with short-fiber South American eucalyptus at 20% *vs*. 75%, 15% *vs*. 80%, or 10% *vs*. 85%, the hand-felt softness of such products was significantly better than the original northern pine + acacia + Asian eucalyptus blend. This could have been due to the combined effects of fiber morphology and less refining.

As shown in Table 2, when the proportion of long fibers persistently decreased, the tensile MD/CD ratio also accordingly decreased. Upon adjusting the jet-to-wire speed ratio by on-site workers, the ratio showed a slight improvement, albeit not significantly. Further, a lower MD/CD tensile strength ratio indicated less of a strength differential between MD and CD, and the hand-felt softness tended to be coarser. These results explained why the 10% long-fiber blend production condition performed more poorly with regard to hand-felt softness than the higher long-fiber blend groups. In addition, upon switching to new furnish blends, the water absorbency values increased to >20 mm, which is thought to mainly reflect a reduced degree of refining.

At the same quality level, the economic efficiency analysis indicated that reducing the long-fiber content in the furnish by 10% (from 25% to 15%), and with a cost differential of long- and short-fibers at *ca*. US$ 60 to 100/ton of pulp, the production cost per ton of paper would decrease by US$ 6~10.

CONCLUSION

This study examined the effects of the furnish mix, fiber morphology and pulp refining on the softness of household paper. The laboratory handsheet experimental results indicated that refining significantly reduced the softness of the tissue. At a pulp freeness of <500 mL CSF, the effect was alleviated. The hand-felt softness and bulk softness changed with the fiber’s length-to-thickness ratio; whereas the surface softness appeared to change with the fiber slenderness ratio. On-site production runs indicated that by selecting pulps with higher length-to-thickness and slenderness ratios, and by adjusting the furnish mix and refining intensity, it would be feasible to produce products of higher softness with qualities complying with product specifications. Thus, at the same quality level, the economic efficiency analysis indicated that the production cost of each ton of paper could be reduced by US$ 6~10 by adjusting the pulp blend.

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