Research paper

Weighted Average Fiber Length: An Important Parameter in Papermaking

Vipul Singh Chauhan,[1,4] Nitin Kumar,[1] Manoj Kumar,[2] S. K. Thapar[3]

【Summary】

Long-fibered softwood and bamboo pulps with respective average fiber lengths of 2530 and 1688 μm were blended with eucalyptus pulp of 696 μm in average fiber length. The target was to obtain a weighted average fiber length (WAFL) of the blends similar to acacia pulp at 990 μm average fiber length. All pulps were refined with different PFI mill revolutions, and handsheets were produced. The refining behavior, drainage of pulp, and various paper properties (bulk, tensile strength, burst strength, tear index, double fold, Scott bond, air permeability, and formation) were determined and compared. The WAFL had no effect on the refining energy demand or drainage rate of the blended eucalyptus pulp. The intrinsic fiber length of the pulp furnish had greater effects on the paper properties than did the WAFL. Acacia pulp provided lower paper strength compared to eucalyptus pulp at the same refining level. The tear index was higher with acacia than eucalyptus pulp, and after blending with softwood and bamboo, eucalyptus provided a greater tear index than did acacia, which illustrates the effect of the WAFL on the tear index of paper. At 500 mL CSF, respective increases in the tear index of paper made from eucalyptus pulp blended with softwood and bamboo pulps were 3 and 20% compared to that of acacia pulp.

Key words: bamboo, hardwood, paper properties, refining, softwood, weighted average fiber length.

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研究報告

重量平均纖維長度：製漿造紙中的一個重要參數

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摘　要

平均纖維長度分別為2530及1688 μm之長纖維針葉樹漿與竹漿，分別與平均纖維長度為696 μm之桉樹漿予以混抄，其主要目標為使混抄漿料之重量平均纖維長度(WAFL)與平均纖維長度為990 μm之相思樹漿相似。所得各組漿料施以不同PFI轉數予以精鍊，並抄製成紙，同時檢測並比較打漿性、紙漿濾水性及紙張性質(嵩度、抗張強度、破裂強度、撕裂指數、耐摺力、Scott內部結合強度、透氣度及交織性質等)。混抄之桉樹漿，對於精鍊時之能源需求或是紙漿濾水速率均無任何影響，顯示重量平均纖維長度對此二性質無影響。紙漿中原有纖維長度對於紙張性質影響較重量平均纖維長度為大。相同打漿度下，相思樹漿較桉樹漿強度為低。而在撕裂指數方面，相思樹漿較桉樹漿為佳。再者，將桉樹漿分別混抄針葉樹漿及竹漿，二者所得之撕裂指數較相思樹漿為佳，顯示重量平均纖維長度會影響紙張之撕裂指數。且於游離度500 mL CSF時，桉樹漿分別混抄竹漿及針葉樹漿，則所得之撕裂指數較相思樹漿多3及20%。

關鍵詞：竹類、闊葉樹、紙張性質、精鍊、針葉樹、重量平均纖維長度。

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INTRODUCTION

The demand for quality paper is increasing day by day. At the same time, the entire manufacturing process needs to be as cost-effective as possible. Process development plays a key role in achieving an efficient process for manufacturing paper. Fine papers are typically produced from hardwood pulp blended with small amounts of softwood pulp. Long and coarse softwood fibers act as a reinforcing material, whereas short and fine hardwood fibers form a good printing base. The blending of hardwood and softwood fibers changes the overall morphology of papermaking fibers. The addition of a small amount of long fibers with short fibers will increase the weighted average fiber length (WAFL) of mixed pulp suspensions. The blending of pulps will also affect fiber properties such as the fiber width, coarseness, flexibility, etc. The blending of softwood and hardwood pulps is generally done based on the ability to operate paper machines, process parameters, and end-product properties. Various researchers have studied the effects of blending hardwood and softwood fibers on the refining energy when blended before or after refining (Kibblewhite 1994, Brindley and Kibblewhite 1996, Mansfield and Kibblewhite 2000, Gao et al. 2009, Chauhan et al. 2011). Researchers have been working on different aspects of fiber morphology and its impacts on paper properties. So far, little knowledge is available on the WAFL of blended pulp furnishes and its effect on blended pulps and paper properties.

Saharinen et al. (2009) showed that the

fiber length of bleached softwood kraft pulp is only critical for fiber flocculation and strength properties, and not for the paper's surface properties. The fiber length distribution does not play a role in paper properties, and measurements of average values appear to be sufficient to predict changes in paper properties.

Fiber length and fiber coarseness have significant effects on the tearing and tensile strengths of paper. In a weakly bonded sheet, fiber length has a greater effect on the tearing strength, and the effect decreases with an increase in the fiber-bonding strength. The increase in coarseness of the fibers was found to result in increased tearing strength and decreased tensile strength (Seth 1995, Liu et al. 2006).

The effect of fiber length on the elastic modulus of paper sheets selected at random was examined by Kimura and Uchimura (1995). The finite fiber length model indicated that the elastic property of paper in a lower range of sheet densities depends on the length of the constituent fibers (Xu et al. 1998).

Influences of the parameters of fiber length, coarseness, and length distribution on the properties of paper produced from unbeaten hardwood and softwood pulps were investigated by Song et al. (1992). The relationship between the length and coarseness of an average weight fiber was investigated. A comparison of the measured and calculated values of length and coarseness showed a good relationship between the 2 parameters. From regression analyses, it emerged that the tear index was more a function of fiber length than of coarseness. No positive relationship was reported between opacity and coarseness.

Yan et al. (2006) reported that the fiber length, represented as a crowding factor, was the dominant factor affecting fiber suspension flocculation, which was also suggested by an evaluation of the formation of corresponding paper sheets. They also reported that the fiber properties could be controlled to some extent by adjusting the mixing ratio of softwood and hardwood pulps. Thus, fiber suspension flocculation can be manipulated by properly setting the fiber length to improve paper sheet formation.

Hiltunen and Paulapuro (2010) mixed chemical softwood pulp and mechanical pulp, and determined their effects on the fiber length and bonding potential of paper. Fiber length was manipulated by the proportions of various pulps, and the inter-fiber bonding potential by the beating level of the chemical pulp. Web breaks are often initiated by small flaws in paper such as shives, holes, etc. They showed that a higher average fiber length improved the flaw-resisting ability of dry paper. The flaw-resisting ability of reinforced paper could be controlled by modifying the average fiber length of the furnish, which controlled the bonding ability. On the other hand, tensile properties like the elastic modulus are not dependent on fiber length; instead, they depend on fiber segment activation, inter-fiber bonding, and fiber strength.

The literature shows that fiber lengths of individual and mixed pulps have great roles in papermaking. They are more significant when pulps of different fiber morphologies are mixed together. In India, most of the paper industries blend long-fibered softwood pulps or preferably locally available bamboo pulp with short-fibered hardwood or agro-residue-based pulps to obtain paper properties of a desired level. These indigenous fibers contain more fines than fibers available globally, and this also greatly influences the papermaking process and paper properties. Chauhan et al. (2012) showed the effect of primary fines on the refining energy and strength properties of paper when added in different proportions to mixed hardwood pulps. The mixing of pulps is generally performed according to target paper properties. In the present communication, the effects of the WAFL of blended pulps on refining, papermaking and paper properties were studied. Pulps were mixed prior to refining to obtain the desired WAFL and then refined together to obtain various freeness levels. The softwood and bamboo pulp furnishes with comparatively much higher fiber lengths than eucalyptus pulp were blended with the latter to obtain a desired WAFL of the mixture. The WAFL of the mixtures was kept equivalent to the hardwood pulp of acacia furnish.

MATERIALS AND METHODS

Materials

Two hardwood pulps were used in this study: bleached hardwood pulp of acacia furnish was collected from an integrated pulp and paper mill in Indonesia, and bleached hardwood pulp of eucalyptus furnish was collected from an integrated pulp and paper mill in South India. The bleached softwood pulp of pine furnish was collected from an integrated pulp and paper mill in the US. Bleached bamboo pulp was produced in the lab using kraft pulping and a conventional bleaching process.

Blending of pulps

Eucalyptus-based hardwood pulp was blended with softwood and bamboo pulps with a target WAFL equivalent to the average fiber length of acacia pulp, i.e., of around 990 μm. The pulp blending proportions are given in Table 1. The pulps were blended prior to refining.

Methods

The refining of all individual and mixed pulps was carried out in a PFI mill (Hamzern Maskin a/s, Hamar, Norway; PFI mill no. 616) at different revolutions to obtain different freeness levels as per Tappi T 248 sp-00. The pulp freeness was measured on a CSF tester (Universal Engineering Corporation, Saharanpur, India) as per Tappi T 227 om-99. The drainage time of the pulp was determined on a Handsheet former (Universal Engineering Corporation, Saharanpur, India) as per Tappi T 221 cm-99. The fiber morphology (i.e., the average fiber length, fiber width, fines, and coarseness) was determined on an L&W Fiber tester (Lorentzen & Wettre, Kista, Sweden) as per its operating manual. The pulp viscosity was determined using a CED solution as per Tappi T 254 cm-00. Paper handsheets with a basis weight of 60 g m^{-2} were prepared on a Lab Handsheet Former

Table 1. Various characteristics of individual and mixed pulp furnishes

Pulp description	Initial CSF (mL)	Fiber length (μm)	Fiber width (μm)	Coarseness (μg/m)	Fines (%)	Viscosity (cP)
Acacia	680±6	990±2.1	14.0±0.07	94.5±1.6	12.8±0.7	8.2±0.4
Eucalyptus	660±5	696±1.5	13.0±0.07	60.1±1.2	20.2±1.6	11.1±0.7
Bamboo	700±6	1688±2.1	10.8±0.07	93.6±2.5	16.6±0.8	9.2±0.4
Softwood	710±4	2530±4.0	35.5±0.42	157.3±2.2	2.6±0.1	15.9±0.7
Eucalyptus (70.4%) + bamboo (29.6%)	680±5	991±1.2	12.5±0.21	70.8±0.9	18.8±0.9	10.9±0.4
Eucalyptus (84.0%) + softwood (16.0%)	665±4	992±1.7	15.6±0.14	78.1±1.0	17.0±0.2	11.5±1.0

(Universal Engineering Corporation, Saharanpur, India) for all the experiments as per Tappi T 205 sp-02. Sheet pressing and drying were done according to Tappi T 218 sp-02. Sheets were conditioned at 23±1℃ and a 50±2% relative humidity for 24 h following Tappi T 402 sp-98. The methods and instruments used for measuring various properties of paper are given in Table 2. The formation of paper was determined on a Micro Scanner (OpTest Equipment Inc., Hawkesbury, Canada) as per its operating manual. All experiments were carried out in triplicate, and the bars shown in the figures represent the standard deviation on either side of the mean.

RESULTS AND DISCUSSION

Pulp characteristics

The initial freeness values of unbeaten pulps and fiber morphological characteristics are given in Table 1. Respective freeness values of unbeaten acacia, eucalyptus, bamboo, and softwood pulps were 680, 660, 700, and 710 mL. The freeness of eucalyptus blended with bamboo pulp was comparable to that of acacia pulp. The fiber length and width of bleached acacia hardwood pulp were higher than those of bleached eucalyptus hardwood pulp, which showed that fibers of acacia pulp were comparatively longer and wider than those of eucalyptus pulp. As expected, the fiber length and width of bleached softwood pulp were the highest among all pulps used in this study, followed by bleached bamboo and hardwood pulps. Respective fiber lengths of softwood, bamboo, acacia, and eucalyptus pulps were 2530, 1688, 990, and 696 μm. The fiber width of bamboo pulp was the lowest (10.8 μm), even lower than that of hardwood fibers. The coarseness of the softwood pulp was the highest (157.3 μg/m) followed by acacia (94.5 μg/m), bamboo (93.6 μg/m), and eucalyptus (60.1 μg/m) pulps. The fines content was the highest in eucalyptus (20.2%) and the lowest in softwood pulp (2.6%). The CED viscosity of all pulps was in the range of 8~11 cP except for the softwood pulp which had the highest viscosity (15.9 cP). The eucalyptus pulp had a slightly higher viscosity (11.1 cP) than acacia pulp (8.2 cP).

Due to the somewhat longer fiber length of acacia pulp, it was used as a reference pulp, and eucalyptus pulp was respectively blended with 29.6 and 16.0% of bamboo and softwood pulps to obtain a WAFL equivalent to that of acacia pulp, i.e., of around 990 μm. The blending of softwood pulp with eucalyptus pulp increased the fiber width from 13.0 to 15.6 μm. However, the addition of bamboo

Table 2. Methods and instruments used for the testing of various paper properties

Parameter	Tappi test method	Instrument model (Make)
Grammage	T 410 om-98	-
Thickness	T 411 om-97	L&W thickness tester
Stretch	T 494 om-01	L&W tensile tester
Breaking length	T 494 om-01	L&W tensile tester
Tensile energy absorption	T 494 om-01	L&W tensile tester
Burst index	T 403 om-97	L&W bursting strength tester
Tear index	T 414 om-98	L&W tearing tester
Double fold	T 511 om-02	TMI folding endurance tester
Scott bond	T 569 om-00	Scott bond tester
Air permeability	T 460 om-02	L&W air permeance tester

pulp to eucalyptus pulp slightly decreased the fiber width at the same WAFL (Table 1).

Refining energies of the pulps

Chauhan et al. (2011) showed that the fiber length was not affected in blended hardwood and softwood pulps whether refined together or separately in a PFI mill. Similar freeness levels could also be achieved in mixed refined pulps by applying the refining energy equivalent to the energy required to separately refine the pulps. Strength properties of the paper (including the bulk, stiffness, air permeability, and formation) from mixed refined pulps were either better than or comparable to those of the separately refined pulps.

Both hardwood pulps were refined separately at different PFI mill revolutions to understand the refining behavior of each pulp. The mixed pulp furnishes, according to the WAFL, were also refined at different PFI mill revolutions in order to examine the effect of the WAFL of different types of mixed pulps on the refining energy. Refining behaviors of individual and mixed pulp furnishes differed and were dependent on the type of blended pulp furnish. As shown in Fig. 1, the highest energy was required to refine acacia pulp, possibly due to its longer fibers. The energy required to refine eucalyptus pulp was comparatively lower than that of acacia. In spite of the lower viscosity of acacia pulp, it required higher PFI mill revolutions to refine the pulp, which was attributed to the morphological characteristics of the fibers. The blending of softwood and bamboo pulps with eucalyptus pulp did not greatly affect the refining energy demand which was indicated by the similar PFI mill revolutions required for individual eucalyptus and blended pulps. However, in the case of blended pulps, the WAFL was higher than that of eucalyptus pulp, yet the refining energy demands to obtain similar freeness levels were comparable. Similar results were reported by other research groups (Chute 2006, Mohlin et al. 2006, Gao et al. 2009). Mohlin et al. (2006)

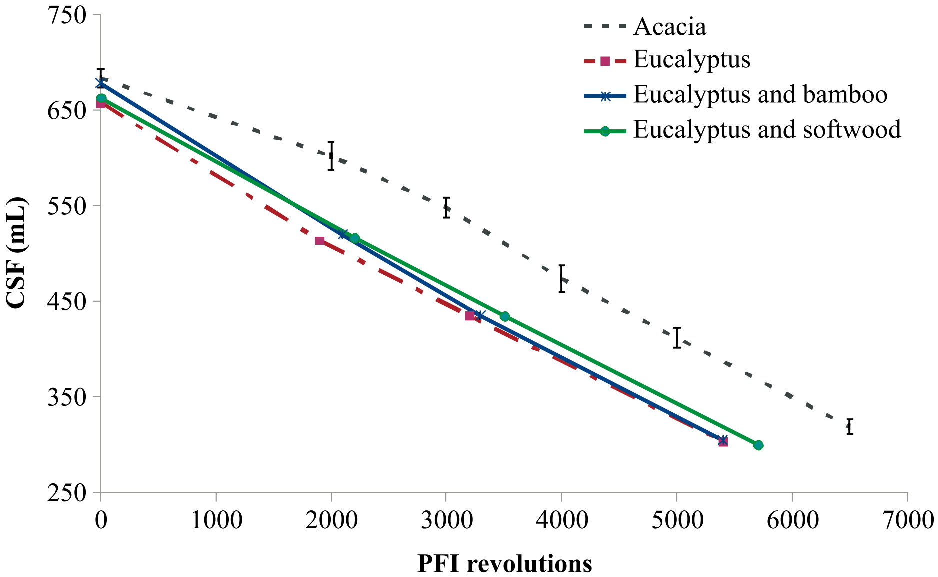

Fig. 1. Effect of the weighted average fiber length on refining energy requirement for different fibers.

showed that the refining response of acacia pulp was slower than that of eucalyptus pulp.

Drainage times of pulps

As shown in Fig. 2, the drainage times of all pulp furnishes increased with refining. It was the highest in the case of acacia pulp at all freeness levels. The drainage time of eucalyptus pulp was much lower than that of acacia pulp when compared at similar freeness levels. At higher freeness levels, the difference in the drainage times of acacia and eucalyptus pulps was greater, and it decreased with decreasing freeness levels. When blending long-fibered pulp furnishes with eucalyptus pulp, drainage times remained almost unchanged. These results indicated that pulps with the same WAFL differently affected the drainage rate. Similar results were presented by Chute (2006).

Physical characteristics of paper

It is known that the bulk of a paper decreases upon refining of the pulp. We also observed similar results. As shown in Fig. 3, the paper bulk decreased upon refining the pulp. This was applicable to all pulp furnishes. The rate of decrease in the paper bulk upon refining was comparable for individual eucalyptus pulp and eucalyptus pulp blended with bamboo and softwood pulps. The bulk of all pulp furnishes was closely comparable at higher freeness levels; however, it rapidly decreased in cases of individual eucalyptus pulp and blended eucalyptus pulps. Similar results were also reported by Perng et al. (2009), who showed that under identical pulp freeness values, hardwood pulps produced papers with higher bulk than those of softwood pulps, which indicated that the blending of hardwood fibers with long-fibered pulps will reduce the paper bulk. When softwood pulps were individually blended with hardwood pulps, the pulp furnishes generally showed no improvement in the paper bulk. They also showed that the fiber cell wall thickness influenced the compression properties and conformability of the paper sheets, and hence impacted the bulk of the resulting paper.

The stretch properties of sheets made

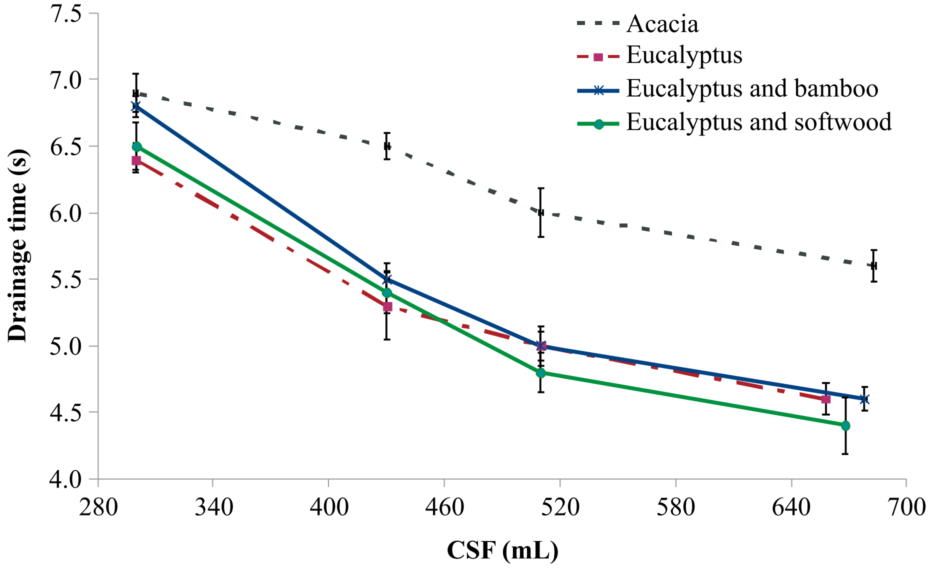

Fig. 2. Effect of the weighted average fiber length on the drainage time of pulp.

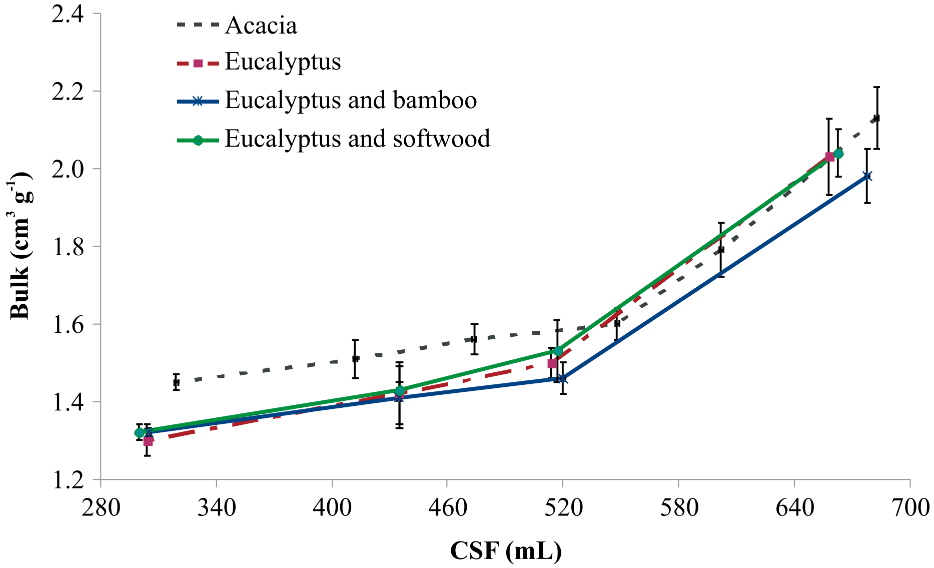

Fig. 3. Effect of the weighted average fiber length on the paper bulk.

from unbeaten fibers are primarily influenced by the fiber length and fibril angle. After beating, the effect of fiber length becomes negligible, and the fibril angle becomes the single dominant variable (Horn 1978). As shown in Fig. 4, elongation of the paper was comparable in cases of all pulp furnishes at higher freeness levels and increased rapidly upon refining. At lower freeness levels, it was little higher with eucalyptus than acacia pulp. When blending softwood and bamboo pulps with eucalyptus pulp, the elongation slightly increased, mainly at lower freeness levels. There was not much effect of the type of blended pulp furnish (softwood or bamboo) on the elongation of paper.

Tensile and bursting strengths of pulps are 2 properties highly dependent upon inter-fiber bonding. Generally, bursting and tensile strengths of sheets made from hardwoods respond to the same fiber morphological effects as do softwoods. Bursting and tensile strengths, which are dependent on the formation of fiber-to-fiber bonds, are greatly influenced by fiber length and the cell wall thickness (Horn 1978). The breaking length, tensile energy absorption (TEA), and burst index of paper increased upon refining for all pulp furnishes. As shown in Fig. 5, the breaking length of sheets made from eucalyptus pulp was higher than that of acacia pulp below a freeness (CSF) level of around 500 mL. This was due to greater fibrillation in eucalyptus fibers at lower freeness levels compared to acacia fibers. The breaking length further increased after blending softwood and bamboo pulps with eucalyptus pulp. At freeness levels of < 500 mL, it was observed that acacia pulp had comparatively lower breaking lengths than eucalyptus pulp; however, the former had a higher WAFL. Similar to the breaking length, the TEA of sheets was also higher for eucalyptus pulp than acacia pulp (Fig. 6). It was further improved by blending long-fibered pulp furnishes with eucalyptus pulp. The highest TEA was observed after blending bamboo pulp than softwood pulp. Similar results were also achieved for the burst index of paper (Fig. 7). At lower freeness levels the difference in burst index values was higher

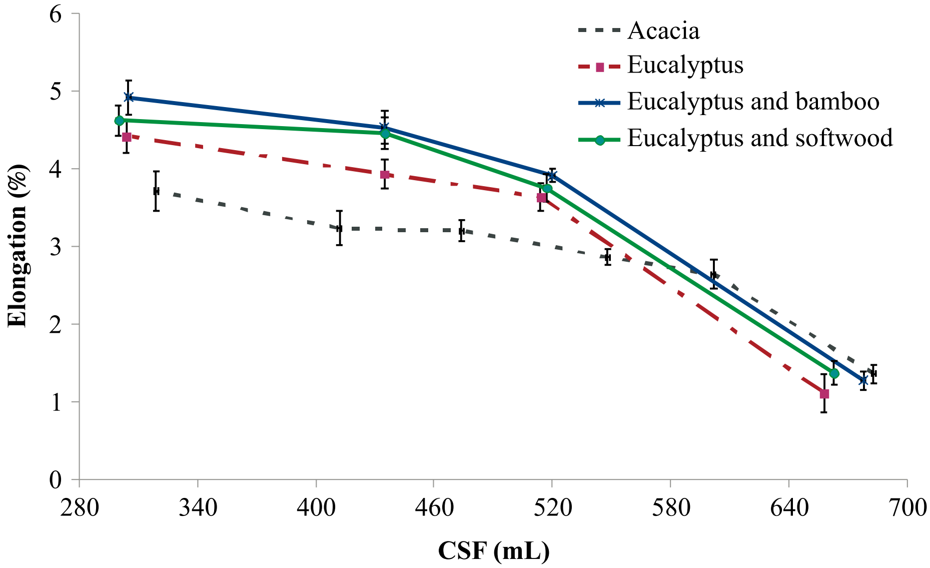

Fig. 4. Effect of the weighted average fiber length on the paper elongation.

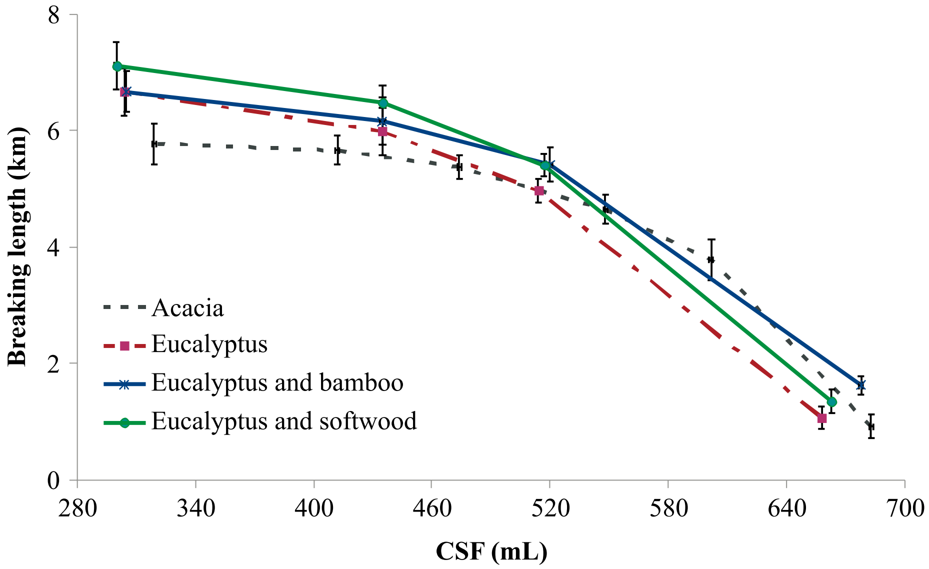

Fig. 5. Effect of the weighted average fiber length on the breaking length of paper.

compared to that at higher pulp freeness values. Initially, the burst index of unrefined pulps was quite low and increased upon refining of the pulps. At 430 mL CSF, the burst index was the highest for blended pulps, followed by eucalyptus and acacia pulps.

The tear strength of a pulp depends upon the fiber morphology. A higher fiber length will result in a higher tear index. The addition of fines to the pulp will reduce the average fiber length, and hence will negatively affect the tear strength (Chauhan et al. 2012).

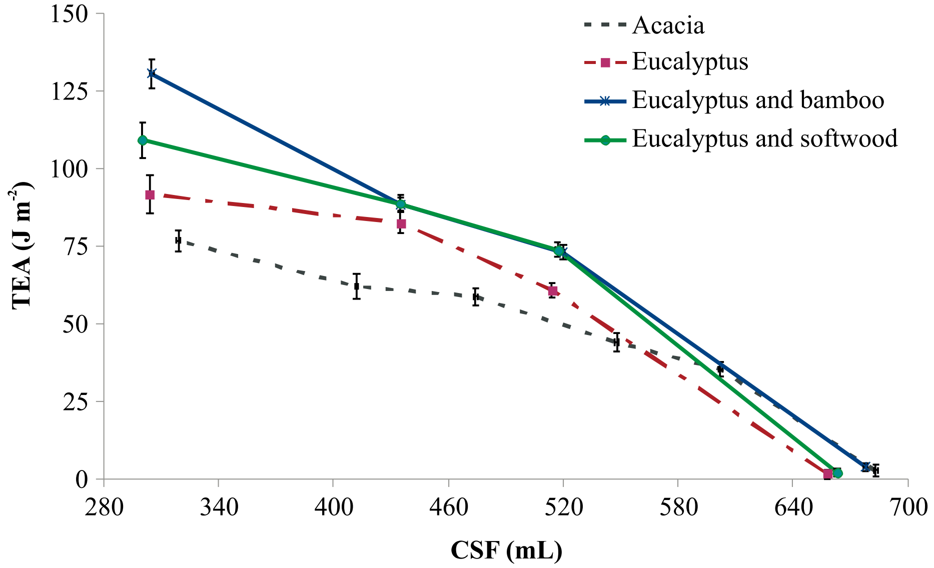

Fig. 6. Effect of the weighted average fiber length on the tensile energy absorption (TEA) of paper.

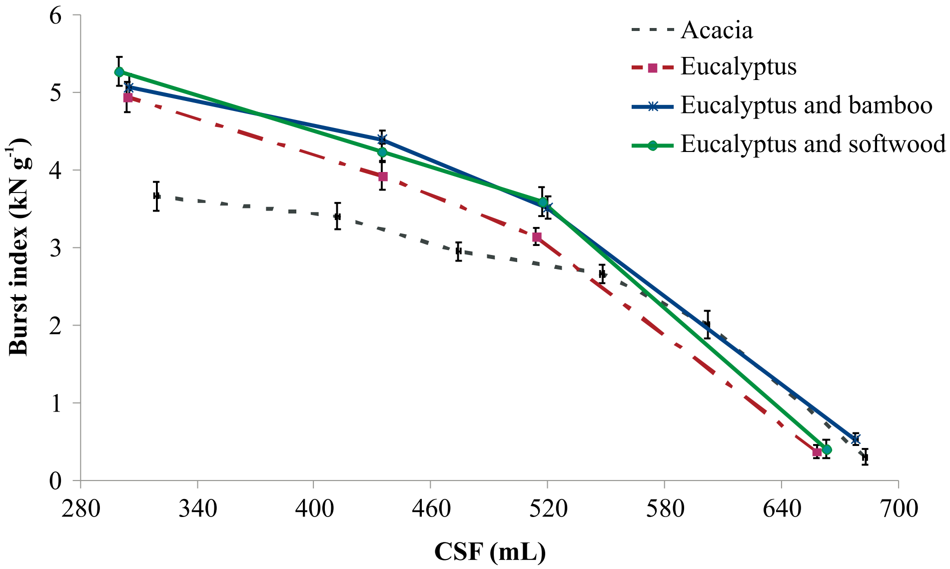

Fig. 7. Effect of the weighted average fiber length on the burst index of paper.

Similar results were also obtained from our experiments. As shown in Fig. 8, when the tear indices of both hardwoods were compared, it was observed that it was higher for acacia due to its higher WAFL than eucalyptus. The decreasing trend in the tear index of paper made from acacia and eucalyptus pulps on refining differed. The tear index of eucalyptus pulp increased with a decrease in the freeness (CSF) to around 500 mL, and then began to decrease with a further decrease in the freeness, whereas that of acacia pulp

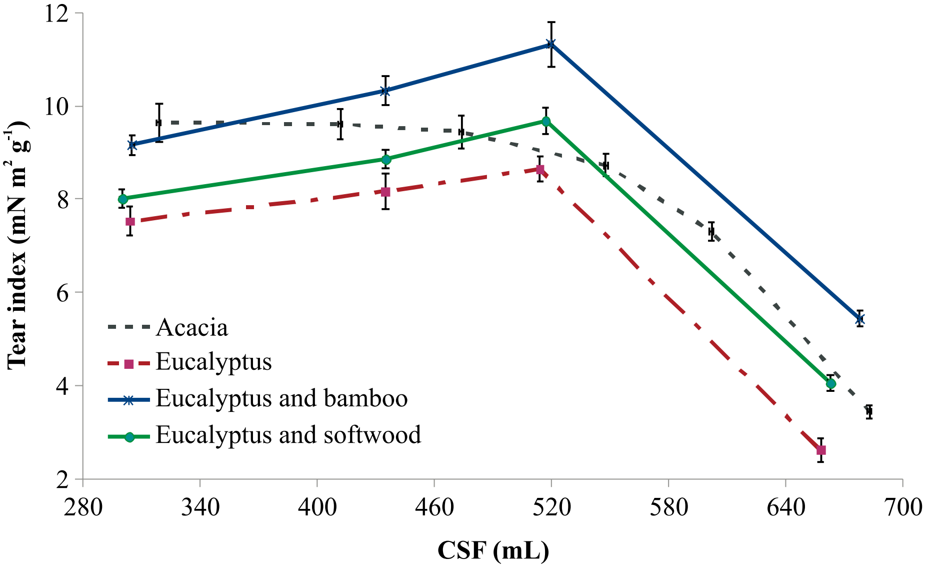

Fig. 8. Effect of the weighted average fiber length on the tear index of paper.

rapidly increased up to a 500 mL freeness level and then increased at a lower rate. When blending long-fibered pulp furnishes with eucalyptus pulp, the tear index increased. It was higher after blending bamboo fibers than softwood fibers. Even at the same WAFL, the tear index was highest with eucalyptus and bamboo blended pulp furnishes. The increase in the tear index after blending long-fibered pulps was due to an increase in the proportion of fibers with higher intrinsic strength (Manfredi 2006). Horn (1978) showed that the tear strength of paper made from hardwood fibers mainly depends upon the fiber length, whereas with softwoods, the cross-sectional area and cell wail thickness are dominating variables. Similar results were also reported by Song et al. (1992) for hardwood and softwood pulp blends. Other factors exhibiting great influences on the tear strength of beaten pulps are the cross-sectional area of fibers and the fibril angle.

As shown in Fig. 9, the double fold of paper was comparatively higher with eucalyptus pulp. The double fold further increased after blending bamboo and softwood fibers in the eucalyptus pulp; the former blends gave comparatively higher double-fold values. The rate of increase in the double-fold values for pulp refining was much higher with bamboo blended with eucalyptus pulp.

As shown in Fig. 10, similar to other strength properties, the internal bond strength (Scott bond) of the sheets was also higher with eucalyptus than acacia pulp. The blending of bamboo and softwood fibers with eucalyptus fibers further increased the Scott bond of paper; similar to previous results, the former provided higher internal strength to the paper. Rates of increase in Scott bond values with eucalyptus, bamboo, and softwood fibers also increased with pulp refining.

A higher number of seconds for the air permeability values means a paper is more resistant to air penetration. As shown in Fig. 11, air permeability values of paper made from all individual and blended pulp furnishes were comparable up to a freeness level of around 500 mL. The value of air permeability rapidly increased with further decreases in the

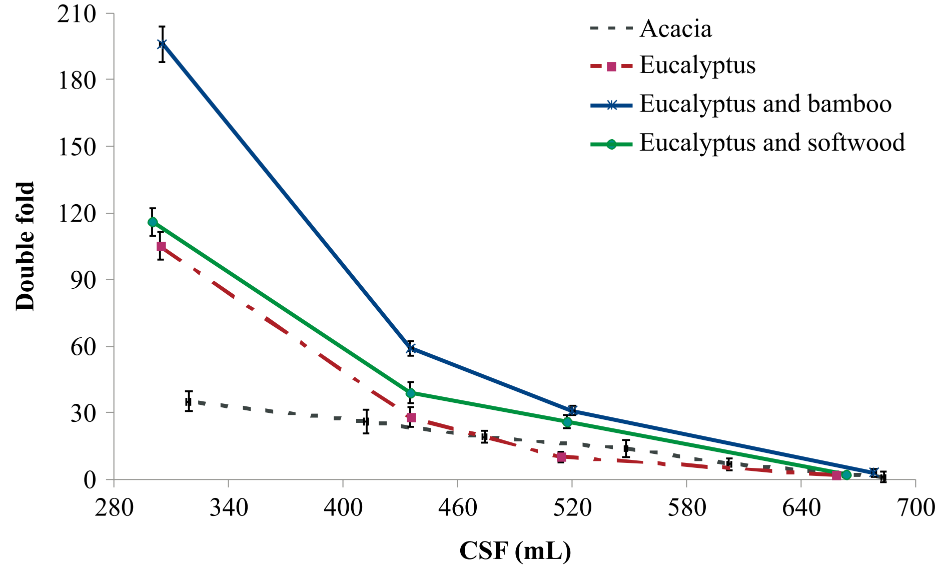

Fig. 9. Effect of the weighted average fiber length on the double fold of paper.

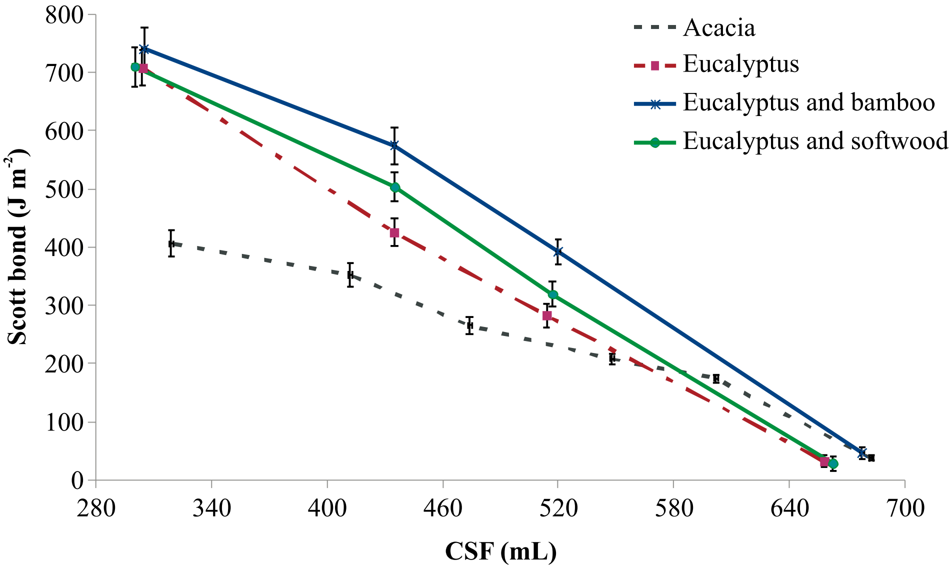

Fig. 10. Effect of the weighted average fiber length on the Scott bond of paper.

freeness of the pulp, indicating that the porosity of the paper decreased with pulp refining. The increase in air permeability values was highest with eucalyptus and bamboo blended pulp furnishes, presumably due to their higher fines content. Bamboo pulp provided a denser sheet of fibers which was responsible for higher air permeability values in seconds, i.e., lower air permeability. Similarly, Perng et al. (2009) showed that with a higher degree of refining, the pulp freeness was lower, rendering tighter-textured sheets that were more resistant to air flow, i.e., less permeable to air. Under identical freeness values, softwood

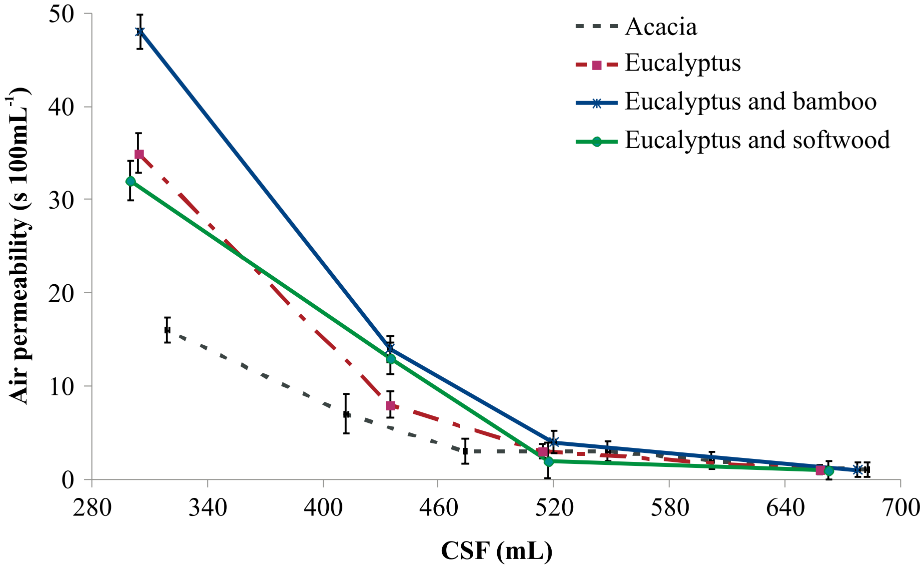

Fig. 11. Effect of the weighted average fiber length on the air permeability of paper.

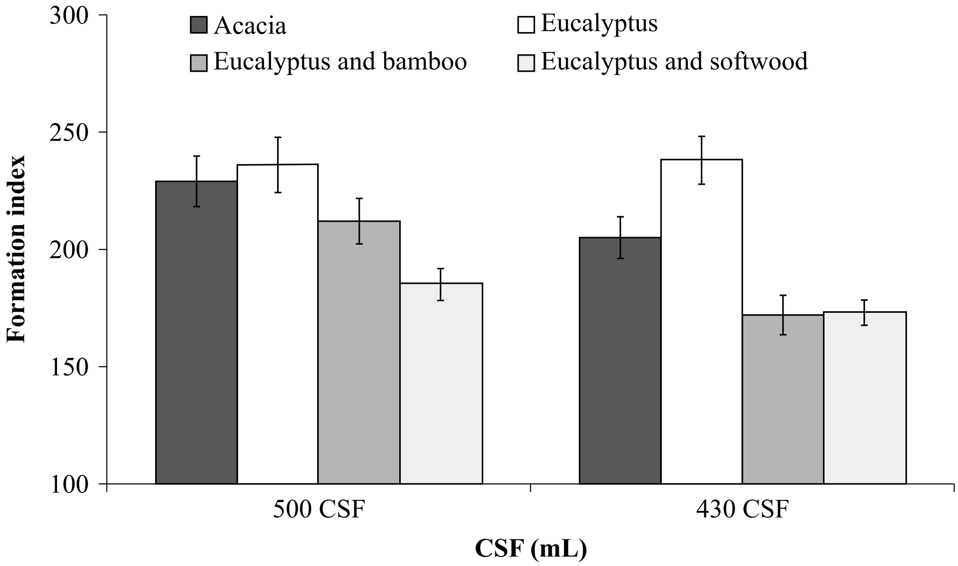

Fig. 12. Effect of the weighted average fiber length on the formation of paper.

pulp had greater air permeability values than did hardwood pulps.

Generally, the formation of paper is improved by the generation of fines content in the pulp furnish, through filling in gaps within the paper matrix. This phenomenon was measured in terms of the formation index. Higher formation index values mean better formation. The formation index was measured at freeness levels of 500 and 430 mL. As shown in Fig. 12, the formation index of paper was the highest with eucalyptus, followed by acacia, and blended pulps. Possibly, the random fiber length distribution of bamboo fibers throughout the sheet structure was responsible for the lower paper formation values. Yan et al. (2006) reported that the effective fiber length of softwood and hardwood pulp blends could affect paper formation. Paper sheet formation can be improved by setting the fiber length and controlling fiber suspension flocculation.

CONCLUSIONS

Fiber morphology has a great role in the development of paper properties. Fibers of different raw materials with similar WAFLs affect paper properties differently. Even fibers of 2 different hardwood pulps, i.e., acacia and eucalyptus, with different average fiber lengths affected the paper properties differently. The intrinsic strength and morphological characteristics of fibers play key roles in the development of paper strength. Paper sheets made from eucalyptus hardwood fibers of lower fiber length had higher paper strength than those from long-fibered acacia pulp. The blending of long fibers with eucalyptus pulp did not greatly affect the refining energy demand. The average fiber length was responsible for the drainage of water from the pulp furnishes rather than increasing the fiber length with blending fibers of different natures.

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