Agr. Nat. Resour. 54 (2020) 287–294

AGRICULTURE AND NATURAL RESOURCES

Journal homepage: http://anres.kasetsart.org

Research article

Effect of long-fiber hardwood kraft pulp from *Baccaurea ramiflora* Lour. on handsheet properties of pulp blends

Theerat Ardsamang*, Pratuang Puthson, Phichit Somboon

Department of Forest Products, Faculty of Forestry, Kasetsart University, Bangkok, Thailand.

Article Info

Article history:
Received 4 June 2019
Revised 22 July 2019
Accepted 29 July 2019
Available online 30 June 2020

Keywords:
Baccaurea ramiflora
Fiber morphology
Pulp blend
Pulp freeness
Pulp strength

Abstract

The effect was investigated of long-fiber kraft pulp obtained from *Baccaurea ramiflora* Lour. on the drainability and strength properties of handsheets produced from its blends with either short-fiber hardwood or long-fiber softwood kraft pulps. The *B. ramiflora* pulp had a wide fiber-length distribution, long fiber length (2.06 mm), high fiber coarseness (0.182 mg/m) and high beatability due to its significantly higher fines content (25.5%), and moderate strength with a high tear index. Blending the long-fiber pulp with other long-fiber pulp caused a linear change in the freeness of the pulp blend. On the other hand, short-fiber and long-fiber blending resulted in a rapid decrease in the freeness of pulp blends for up to 70% low-freeness pulp, but a slower change was observed from 70% to 100%. The addition of the high-strength (softwood) pulp to the low-strength (hardwood) pulp or moderate-strength (*B. ramiflora*) pulp caused a rapid increase in the tensile and tear indices for up to 70% softwood content, but only a slight change upon greater blending up to 100%. While the results of the folding endurance tests were different to those for the tensile and tear indices, the burst index increased linearly. Adding moderate-strength pulp from *B. ramiflora* into low-strength pulp from hardwood resulted in slight changes in the tensile index, burst index and folding endurance of the pulp blends, while the tear index increased rapidly. The *B. ramiflora* pulp could be utilized in containers requiring high tear resistance, in high-softness tissue papers, in filter papers and in cement-based composites.

Introduction

Paper consists of cellulose fibers called “paper pulp” that are bonded to each other in a network that forms a sheet (Islam and Jahan, 2001). Through the choice of different raw materials and fiber pretreatments, paper can be obtained with a wide range of different properties. Different types of paper pulp are commonly mixed together to give the desired paper properties; long-fiber pulps provide strength while short-fiber pulps give good optical and printing properties; however, the relationship between paper strength properties and the blended pulps is complicated and depends on fiber behavior (Fagbemi et al., 2014). Consequently, it is necessary to investigate the properties of different pulps and their blends for making paper.

In general, the initial pulp properties are the main factors determining blended pulp properties such as fiber length, fiber width, coarseness and the intrinsic strengths. The blending of short-fiber and long-fibers changes the structure profile of papermaking fiber exerting influence on the uniformity of the paper and results in a crowding factor (Kerekes and Schell, 1995). Fiber from different raw materials with similar weighted average fiber lengths affects paper properties differently. For example, Chauhan et al. (2013) reported that paper sheets made from eucalyptus hardwood fiber of lower fiber length had

* Corresponding author.
E-mail address: ffortra@ku.ac.th (T. Ardsamang)

https://doi.org/10.34044/j.anres.2020.54.3.08

higher paper strength than sheets made from long-fiber acacia pulp. Pulkkinen et al. (2010) report that the high value of fiber coarseness increases the stretch potential and consequently, the fibers might not flex elastically under mechanical stress in the refiner and that thick-walled fiber showed hardly any collapse and resulted in poor fiber bonding in a sheet structure and had a lower density.

It has long been recognized that generally, the relationships of fiber characteristics to hardwood pulp properties are not as strong as those for softwood pulp (Horn, 1978). The presence of a high percentage of parenchyma (fines) was detrimental to paper strength as tear strength was influenced primarily by fiber length while burst and tensile strengths were influenced primarily by a combined effect of fiber length and cell wall thickness (Horn, 1978).

Long-fiber pulps are mainly produced from softwood, which is not available for pulp and paper production in Thailand and therefore, in 2017 more than 0.35 million t of long-fiber softwood pulp was imported from other regions (Thai Pulp and Paper Industries Association, 2019). Although, hardwood tree species dominate in Thailand, the applicability of long-fiber hardwood pulp for papermaking has not yet been studied. Thus, the investigation of an indigenous hardwood species as an alternative source of long-fiber pulp for the domestic paper industry could be of great benefit.

The objective of this study was to investigate the effects of long-fiber kraft pulp from *Baccaurea ramiflora* Lour. (Thai name: 'mafai'), an indigenous hardwood species in South and Southeast Asia, on the handsheet properties of its pulp blends with either hardwood or softwood market pulps.

Materials and Methods

Pulp samples

Three initial pulps were used in this study. Bleached *B. ramiflora* kraft pulp (BR) was prepared using a 7 L vertical rotating digester with 22% active alkali and 25% sulfidity (as Na_2O) at 165°C. The cooking time was controlled using an H-factor of 1,500. The pulp sample was then bleached using elementary chlorine-free bleaching and the O-D_0-E_P-D_1-E_2-D_2 sequence (D = chlorine dioxide, E = alkaline extraction with hydrogen peroxide and O = oxygen delignification stage) to the target brightness of 88% ISO and stored in a refrigerator at 4°C until used. The detail for preparing bleached *B. ramiflora* kraft pulp has been described in Puthson et al. (2019). The other commercial pulps were bleached short-fiber hardwood kraft pulp (HW) produced from eucalyptus wood and bleached long-fiber softwood kraft pulp (SW) produced from pine and spruce (50:50).

Fiber morphology analysis

The fiber morphology of the pulp samples was analyzed according to the standard of International Organization for Standardization (2011) using a fiber quality analyzer (FQA-360; OpTest Equipment; Canada) to determine the fiber length, fiber width, fines content (ISO 16065-1; International Organization for Standardization, 2011) and fiber coarseness (ISO 23713; International Organization for Standardization, 2011).

Pulp blending

The two market pulp samples were disintegrated by tearing them into small pieces and soaking overnight, followed by disintegration to 1.5% consistency using 30,000 revolutions in a disintegrator (Regmed; Brazil). To improve the pulp strength, three pulp samples were subsequently beaten separately to obtain a pulp of the desired freeness using a PFI mill (Kumagairiki; Japan) according to ISO 5264-2 (International Organization for Standardization, 2011). The number of beating levels was chosen to obtain the maximum strength properties and beatability. Beating revolutions of 9,050, 9,300 and 7,540 were used for the softwood, hardwood and *B. ramiflora* pulps, respectively, to obtain initial freeness values of 525, 409 and 321, respectively. This indicated that softwood could form a high-freeness, long-fiber pulp, *B. ramiflora* a low-freeness, long-fiber pulp and hardwood a low-freeness, short-fiber pulp. Beaten *B. ramiflora* pulp was blended with either beaten hardwood or softwood pulps at ratios of 0:100, 30:70, 70:30, and 100:0 based on oven-dry weight percentage. The papermaking properties of the blended pulps were determined as follows: pulp freeness (ISO 5267-2; International Organization for Standardization, 2011) using a freeness tester (Lorentzen & Wettre; Sweden), laboratory sheets (ISO 5270; International Organization for Standardization, 2011), apparent density (ISO 534; International Organization for Standardization, 2011), light-scattering coefficient (ISO 9416; International Organization for Standardization, 2011) using a brightness tester (Technidyne; USA), tensile index (ISO 1924-2; International Organization for Standardization, 2011) using a tensile tester (Thwing-Albert; USA), folding endurance (ISO 5626; International Organization for Standardization, 2011) using a folding tester (Kumagairiki; Japan), tear index (ISO 1974; International Organization for Standardization, 2011) using a tear tester (Lorentzen & Wettre; Sweden) and burst index (ISO 2758; International Organization for Standardization, 2011) using a burst tester (Lorentzen & Wettre; Sweden).

Statistical analysis

Analyses of variance were applied to compare means in fiber morphology and papermaking properties between samples. Duncan's multiple range test was used to test for differences between means at a significance level of $p < 0.05$. The experimental data obtained from the physical properties of pulp blend were used to develop the model based on the 2^{nd} order polynomial regression technique.

Results and Discussion

Fiber characteristics of initial pulps

The effect of pulp blending on the quality of the paper produced strongly depends on the quality of the starting materials. Fiber length is the most important fiber attribute in determining pulp quality based on reinforcement, runnability, coarseness, conformability, bonding capacity, fiber strength, fiber flexibility and furnish compatibility (Mansfield et al., 2004). Fig. 1 shows that *B. ramiflora* pulp had a wide fiber-length distribution, similar to that of long-fiber softwood, while the fiber-length distribution of short-fiber hardwood was narrow.

The average fiber length of the *B. ramiflora* pulp was 2.060 mm, which was comparable to that of the softwood pulp but much longer than that of the hardwood pulp. The *B. ramiflora* pulp had high fiber coarseness (0.182 mg/m) and significantly high fines content (25.5%) in comparison to both the hardwood and softwood pulps (Table 1). However, the average fiber width of the *B. ramiflora* pulp was 32 µm, which was narrower than for the softwood pulp but wider than for the hardwood pulp. These results showed that the *B. ramiflora* fibers were slender and had much thicker cell walls than the fibers from either the hardwood or softwood pulps.

Physical properties of initial pulps

The bleached *B. ramiflora* hardwood and softwood kraft pulps were beaten to various pulp freeness values using a PFI mill. The *B. ramiflora* pulp showed a notable decrease in the pulp freeness with increasing revolutions (Fig. 2) because of its high primary fines content. This result was consistent with that reported by Seth (2003).

Compared with the hardwood and softwood pulps, the *B. ramiflora* pulp had the lowest handsheet density (Fig. 3), which resulted in low fiber flexibility. The apparent density is an indirect measure of the flexibility of a pulp, with a flexible pulp having a higher apparent density as its fibers are easily compressed into the voids of the sheet (Ibrahim, 2003).

The light-scattering coefficient of the *B. ramiflora* pulp slightly decreased with increased beating (Fig. 4), indicating that the fiber bonding of the *B. ramiflora* pulp developed slowly. Bristow (2009) reported that the degree of fiber bonding and interaction can be indicated by the light-scattering coefficient, which is based on the reflectance of light at the surface of the fibers both externally and at internal cracks in the fiber.

The tensile index of the *B. ramiflora* pulp was significantly lower than that of the softwood pulp but higher than that of the hardwood pulp (Fig 5). The tear index of the short-fiber hardwood pulp was much lower than that of the long-fiber *B. ramiflora* and softwood pulps and increased even after severe beating (Fig. 6), which was consistent with the observation by Fellers (2009). The tear index-tensile index relationship, shown in Fig. 7, indicated that the softwood pulp was the strongest, followed in order by the *B. ramiflora* and hardwood pulps. The burst index results of the three pulps showed similar trends to the tensile index (Fig. 8). The folding endurance of the *B. ramiflora* pulp was comparable to that of the hardwood pulp but much lower than that of the softwood fiber (Fig. 9).

Table 1 Fiber morphology of bleached *B. ramiflora*, hardwood and softwood kraft pulps (mean±SD)

Pulp property	*B. ramiflora* pulp	Hardwood pulp	Softwood pulp
Fiber length, length-weighted (mm)	2.060±0.014 ^{a}	0.774±0.007 ^{c}	2.015±0.010 ^{b}
Fiber width (µm)	32.0±0.2 ^{b}	27.6±0.1 ^{c}	39.6±0.2 ^{a}
Fines (%)	25.5±0.8 ^{a}	2.2±0.1 ^{c}	4.0±0.1 ^{b}
Fiber coarseness (mg/m)	0.182±0.001 ^{a}	0.073±0.000 ^{c}	0.160±0.001 ^{b}

$^{a, b, c}$ = Means with different lowercase superscripts in a row differ significantly ($p < 0.05$)

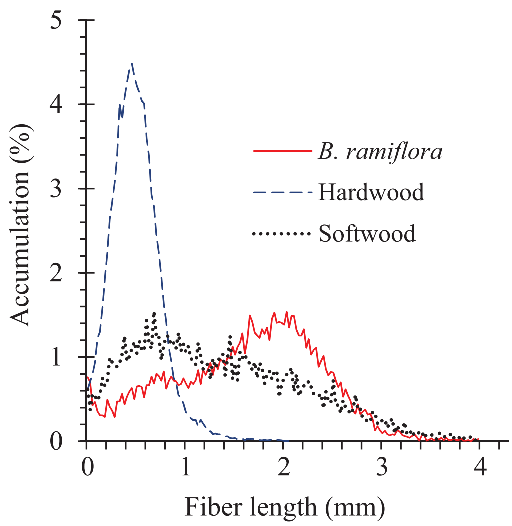

Fig. 1 Fiber-length distributions of bleached *B. ramiflora*, hardwood and softwood kraft pulps

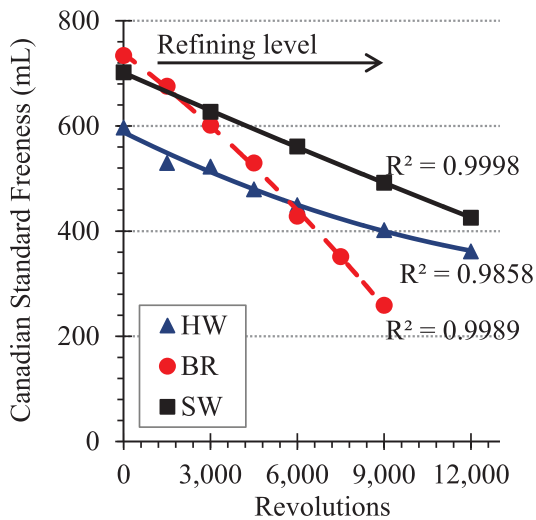

Fig. 2 Pulp freeness of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

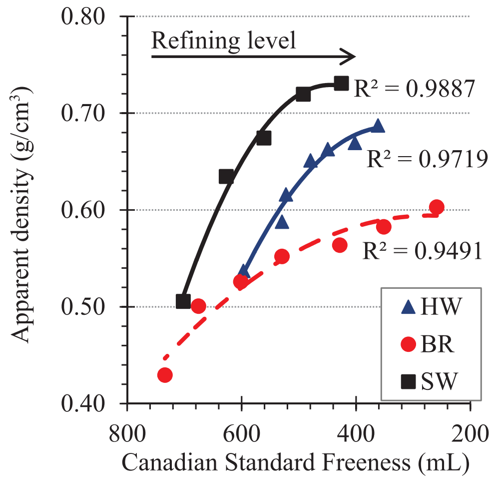

Fig. 3 Apparent density of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

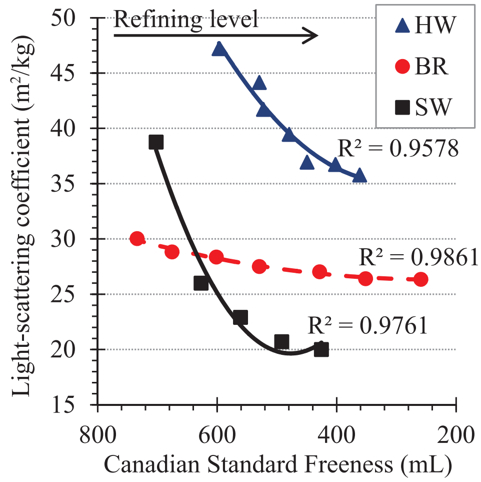

Fig. 4 Light-scattering coefficient of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

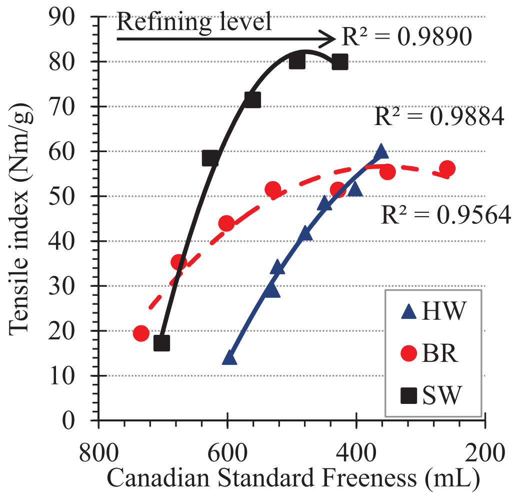

Fig. 5 Tensile index of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

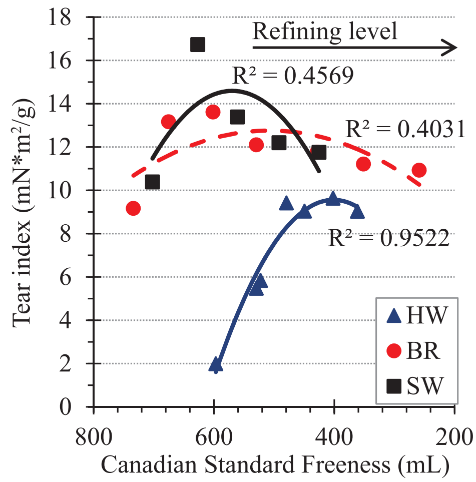

Fig. 6 Tear index of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

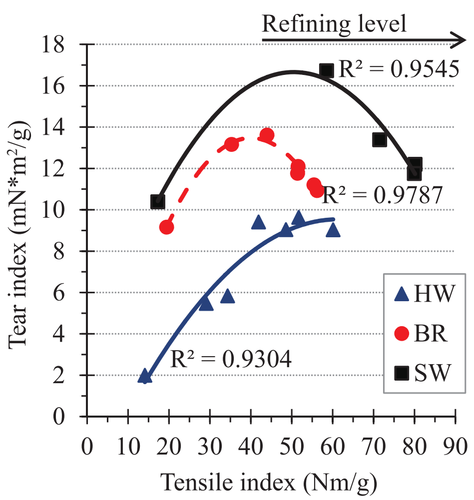

Fig. 7 Tear index-tensile index relationship of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

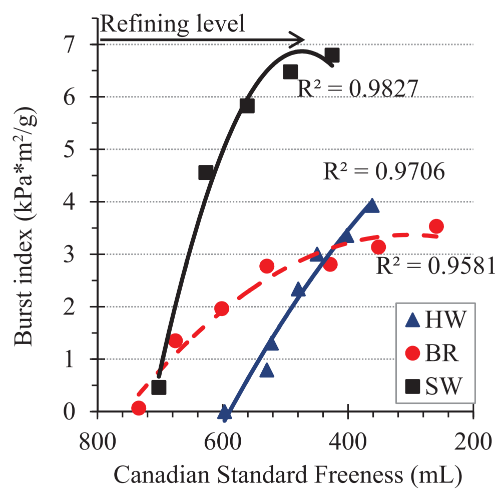

Fig. 8 Burst index of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

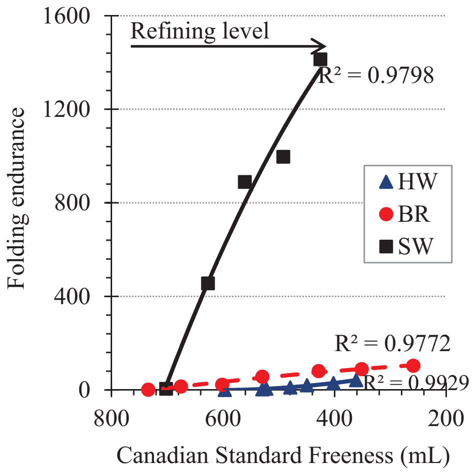

Fig. 9 Folding endurance of bleached kraft pulps from *B. ramiflora* (BR), hardwood (HW) and softwood (SW), where R^2 is the coefficient of determination

Effect of pulp blending on drainability

The freeness of the blended pulps depended on the initial freeness and fiber length of the constituent pulps. The pulp-freeness behavior of the various blends of short and long fibers was unlike that of blends of long fibers with long fibers. The results indicated that blending a long-fiber pulp with another long-fiber pulp changed the pulp freeness linearly. In the BR:SW pulp blends, as both the softwood and *B. ramiflora* pulps are long-fiber pulps, so the freeness decreased linearly as the amount of the *B. ramiflora* pulp in the blends increased (Fig. 10A). The short-fiber and long-fiber pulp blends resulted in reduced drainage of water through the fiber mat. Short fibers play an important role in the reduction of the drainability of blended pulps containing short and long fibers (Panthai and Somboon, 2014). The addition of the *B. ramiflora* pulp to the blend resulted in a rapid decrease in the freeness up to a content of 70% *B. ramiflora* pulp but resulted in only a slight decrease with a further increase in the *B. ramiflora* pulp content up to 100% (Fig. 10A). A similar trend was observed for SW:HW pulp blends (Fig. 10B).

Effect of pulp blending on handsheet properties

Apparent density and light-scattering coefficient

The apparent density and light-scattering coefficient had an almost-linear relationship with the proportions of the three pulps as shown in Figs. 11 and 12, respectively. Adding the *B. ramiflora* pulp to the hardwood or softwood pulps decreased the apparent density. Increasing the *B. ramiflora* pulp content resulted in a decreased light-scattering coefficient in the BR:HW pulp blends and an increased light-scattering coefficient in the BR:SW pulp blends.

Strength properties

The results showed that adding a higher-tensile strength pulp into a lower-strength pulp rapidly increased the tensile strength; for example, by adding the softwood pulp to the BR:SW pulp blends (Fig. 13A) or adding the softwood pulp to the HW:SW pulp blends (Fig. 13B). However, adding the *B. ramiflora* pulp to the BR:HW pulp blends resulted in only minor changes.

The tear index increases with increasing proportions of long fibers in the pulp blends (Korpinen and Fardim, 2009). Adding the softwood pulp to a BR:SW pulp blend resulted in a rapid increase in the tear index, while adding long-fiber (softwood or *B. ramiflora*) pulp to short-fiber (hardwood) pulp initially resulted in a rapid increase in the tear index followed by a slight increase when the proportion of softwood pulp exceeded 70% (Fig. 14).

The burst index had an almost linear relationship with the component proportions of the *B. ramiflora* and hardwood pulps, as shown in Fig. 15A and 15B, respectively. Adding softwood pulp to the BR:SW and HW:SW pulp blends produced a linear increase in the burst index. However, increasing the amount of the *B. ramiflora* pulp in the BR:HW pulp blends resulted in only a slight increase in the burst index (Fig. 15A). The bursting strength had a different trend to the tensile index due to the complex relationship between the fiber properties and the tensile strength (Caulfield and Gunderson, 1988).

The folding endurance slightly increased as the proportion of the higher-folding-endurance pulp in a lower-strength pulp was increased up to 30%, then increased rapidly up to a 100% higher-folding-endurance pulp. However, the individual pulps of *B. ramiflora* and hardwood had almost the same values for folding endurance. Consequently, there was only a minor change in the burst index with changes in the proportions of the individual pulps in the mixture (Fig. 16).

The *B. ramiflora* pulp was composed of slender fibers with very thick cell walls resulting in bulky sheets with a more porous structure. Furthermore, this pulp had high beatability and moderate strength properties with a high tear index. Adding this pulp to a BR:SW pulp blend would increase the bulk of the handsheets while decreasing the strength properties. The addition of the *B. ramiflora* pulp in a BR:HW pulp blend resulted in a large increase in the tear index, but only a small increase in the tensile and burst indices. Thus, this pulp could be utilized in containers requiring high tear resistance, in high-softness tissue papers, in filter papers and as a reinforcement fiber in cement-based composites.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

The authors gratefully acknowledge the Graduate School of Kasetsart University, Bangkok, Thailand for an international publication scholarship. The Trat Agroforestry Research and Training Station provided the wood raw material and Siam Tree Development Co., Ltd. prepared the industrial woodchips.

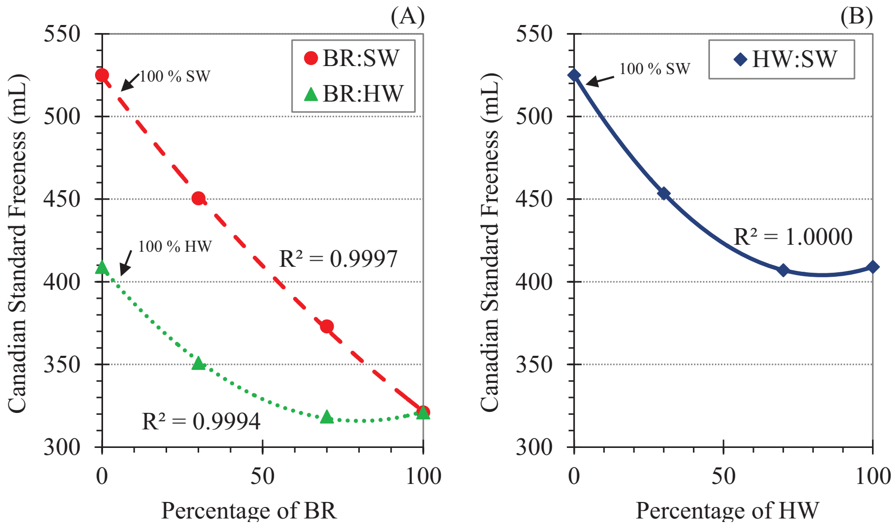

Fig. 10 Freeness of pulp blends at various contents of: (A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

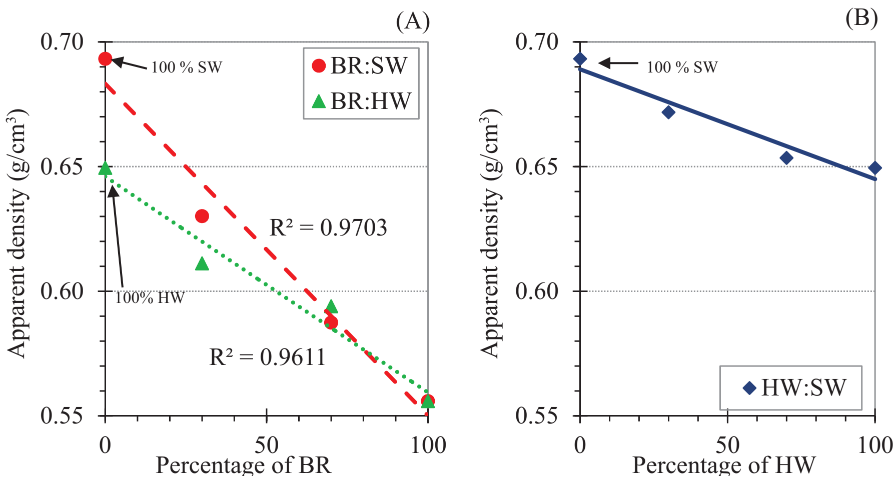

Fig. 11 Apparent density of pulp blends at various contents of: (A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

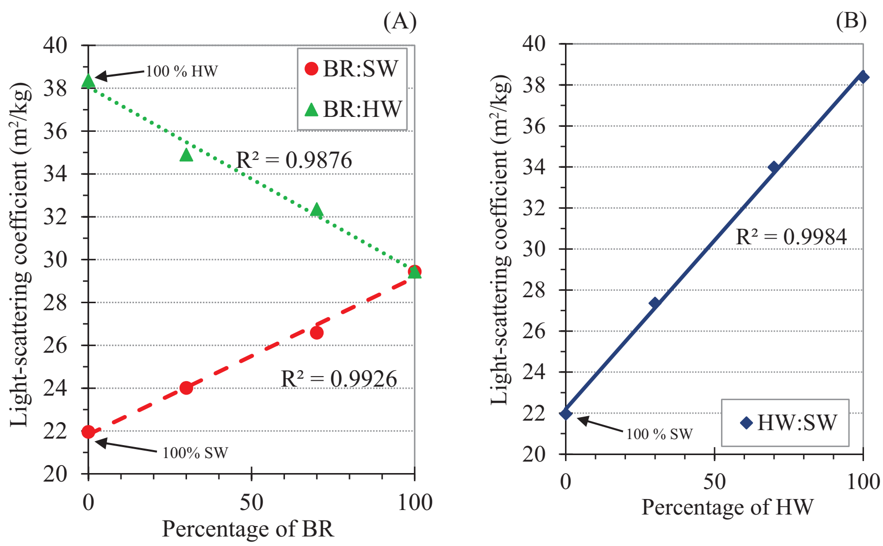

Fig. 12 Light-scattering coefficient of pulp blends at various contents of: (A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

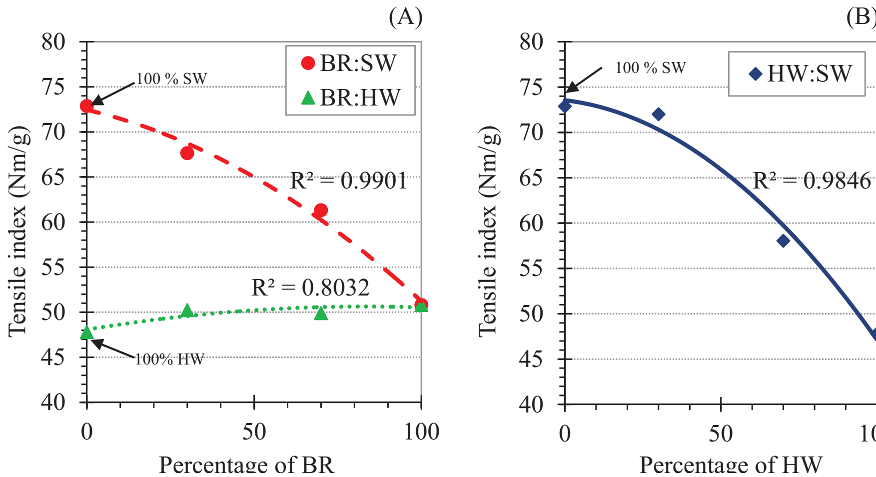

Fig. 13 Tensile index of pulp mixtures at various contents of: (A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

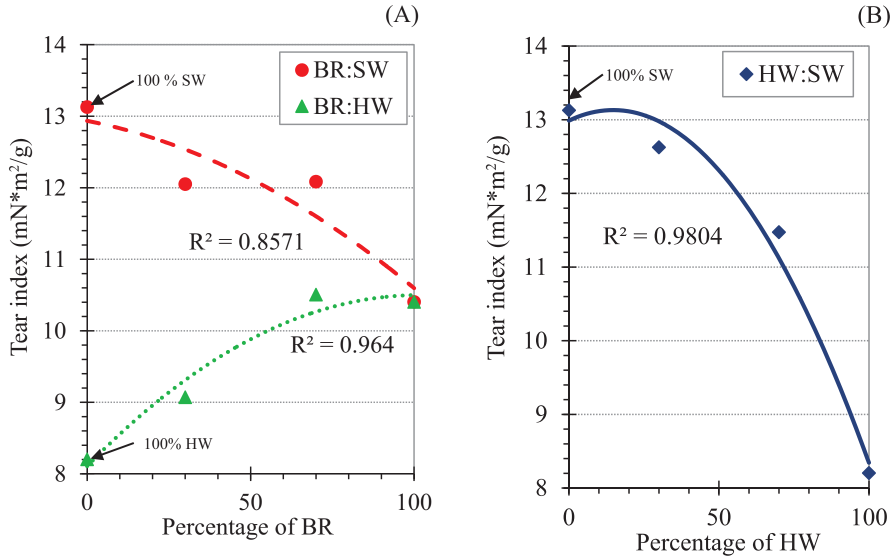

Fig. 14 Tear index of pulp blends at various contents of: A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

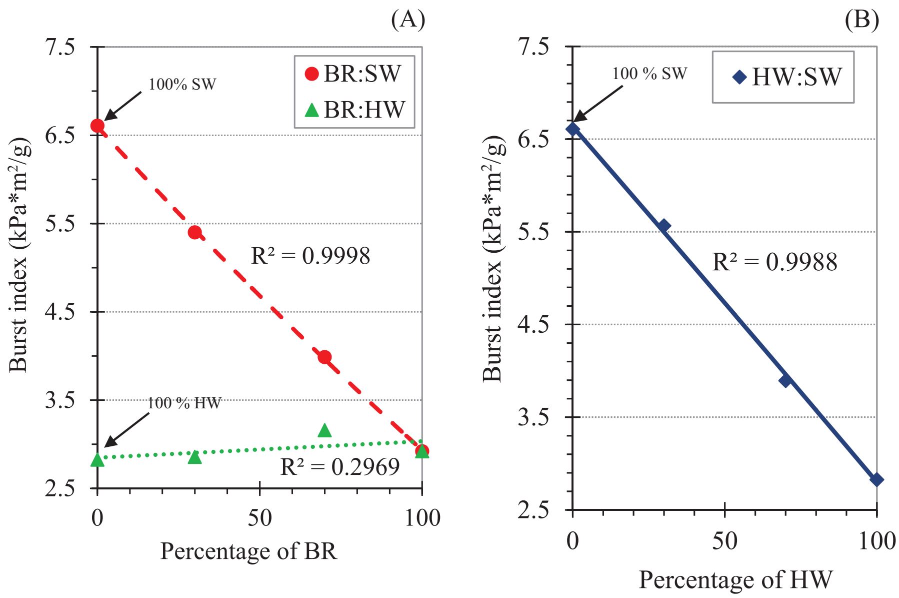

Fig. 15 Burst index of pulp blends at various contents of: (A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

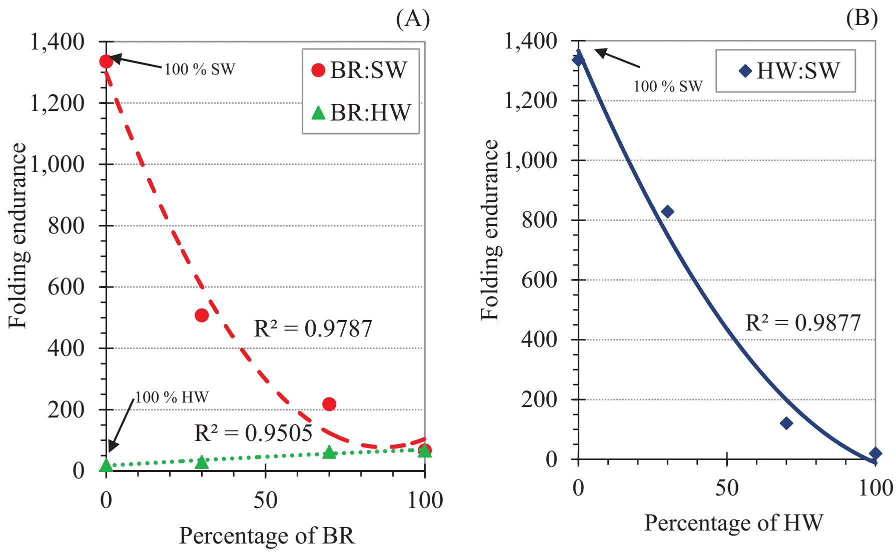

Fig. 16 Folding endurance of pulp blends at various contents of: (A) *B. ramiflora* (BR) and (B) hardwood (HW), where R^2 is the coefficient of determination and SW = softwood

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