Evaluation of Changes in Fold Cracking and Mechanical Properties of High-Grammage Paper Based on Pulp Fiber Modification

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The demand for high-grammage paper, 150 g/m^2 or more, is increasing for product protection and aesthetic value. Fold cracking, resulting from high mechanical pressure during folding, considerably decreases the economic feasibility of such products for papermaking companies. Fold cracking can be reduced through creasing, but defects possibly occur as fiber bonds are broken. In this study, the fold cracking of high-grammage paper that was not treated through creasing was explored. The mechanical and folding properties of six types of pulp fibers were evaluated based on their beating degree. The fines content of the fiber differed according to the beating condition. Using pulp with low fines content improved the folding properties. The mechanical properties of hardwood pulp were enhanced with increased beating degree. The mechanical properties of softwood pulp were considerably increased, and fold cracking occurred with increasing beating degree. Therefore, to improve the fold cracking, beating should be applied appropriately, following the type and mixing ratio of pulp fibers. Finally, softwood pulp mixing is proposed as a strategy to control fold cracking while maintaining the unique characteristics of high-grammage paper.

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Keywords: Fold cracking; Pulp fiber; Beating; Pulp composition; Mechanical properties; Proportional values of change; Pulp species

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INTRODUCTION

The market for recyclable paper materials is expanding due to the increasing awareness of environmentally friendly packaging materials. Packaging specifications continuously change, depending on factors such as consumer requirements and the times. While simultaneously improving the aesthetic effect of the product, the contents must be effectively protected during distribution, and the packaging effect must be preserved. Furthermore, the demand for high-grammage paper is increasing to facilitate product protection and to utilize the distinctive texture of the paper. The high mechanical pressure employed during folding results in fold cracking. Consequently, the economic feasibility of manufacturing this grade of products by paper companies is considerably decreased, because the paper with a basis weight of 150 g/m^2 or more is typically used to produce various materials such as boxes and pamphlets. High-grammage paper has high bulk properties; therefore, during the folding process, a higher tensile stress is generated outside the folding direction, and fold cracking occurs as the paper structure is delaminated (Jopson and Towers 1995; Barbier *et al*. 2002; Rättö *et al*. 2011). Fold cracking can be reduced through creasing; however, creasing is not applicable to certain packaging design wherein aesthetic factors are prioritized. Despite creasing, fold cracking may occur because of changes in paper properties caused by harsh working conditions (high pressure, high speed, linear pressure, *etc*.) or environmental conditions (temperature, humidity, *etc*.) (Lee *et al*. 2008). Therefore, a method for improving folding properties without creasing treatment or under harsher working conditions would be advantageous for high-grammage paper products.

Fold cracking of high-grammage paper is generally affected by the physical properties of low-grade paper and moisture conditions (Carbone 1999); however, the stock preparation conditions (*e.g.*, mixing ratio of pulp fibers, wet strength agent, and fillers) are also known to affect fold cracking (Alam and Toivakka 2011; Youn *et al*. 2012). According to Sim *et al*. (2015) folding properties are improved when the mixing ratio of softwood pulp in the coating paper is increased or when the paper is composed of mechanical or recycled pulp with high bulk properties. Although the occurrence frequency of fold cracking can be controlled according to the raw pulp characteristics, intensive research is necessary for the appropriate selection of pulp fiber raw materials.

In this study, the effects of the properties of pulp raw materials (type of pulp fiber, mixing ratio, and beating degree) on the folding properties of high-grammage paper are evaluated under non-creasing conditions. Tensile strength, breaking length, density, and internal bond strength, which are properties that affect fold cracking, are calculated as proportional values of change and visually expressed. Accordingly, the correlation between the change in the composition of the raw pulp material, its physical properties, and fold cracking is analyzed.

EXPERIMENTAL

Materials

To evaluate the folding properties based on types of pulp fibers, four types of hardwood pulp (Hw-pulp) and two types of softwood pulp (Sw-pulp) used in the industry were prepared. The six types of pulp products composed of both bleached kraft pulp (BKP) and bleached chemi-thermomechanical pulp (BCTMP). The species of each pulp are shown in Table 1.

Table 1. Species and Pulping Methods According to Pulp Type

Symbol	Species	Pulping Method
Hw-A	Eucalyptus	Kraft pulping(bleached)
Hw-B	Eucalyptus	Kraft pulping(bleached)
Hw-C	Eucalyptus	Chemithermomechanical pulping (bleached)
Hw-D	Acacia, Oak	Kraft pulping(bleached)
Sw-A	Lodgepole Pine, White Spruce, Sub-alpine Fir	Kraft pulping(bleached)
Sw-B	Radiata Pine	Kraft pulping(bleached)

Evaluation of Pulp Fiber Properties

The morphological characteristics of pulp fibers differ depending on the type of wood chips, pulping method, and beating degree. A laboratory Hollander beater, which is often called a valley beater (Daewon, South Korea), was used for beating the pulps, and each pulp fiber was beaten to 20°, 30°, and 40° SR. The beating degree of each pulp fiber was evaluated through a Schopper–Riegler freeness tester (ISO 5267-1 1999). The morphological properties, such as fiber length and roughness, of each pulp fiber after beating were analyzed using a fiber length analyzer (MorFi Analyzer, L&W, Kista, Stockholm, Sweden).

High-grammage Paper Forming

Samples were prepared with different types of pulp fibers and at various beating degrees to observe the changes in the pulp fiber properties (Table 2). In addition, high-grammage paper was manufactured under the conditions listed in Table 3 to evaluate the effect of the physical and folding properties by changing the mixing ratio of softwood and hardwood pulps. High-grammage paper samples were prepared with a basis weight of 200 g/m^2 using a laboratory handsheet former. Subsequently, a laboratory roll press was utilized to compress the samples at a pressure of 400 kgf/cm and a speed of 10 m/min. Finally, the compressed samples were dried at 150 ℃ using a cylinder dryer, and the moisture content was uniformly controlled for 24 h under the conditions of 20 ± 5 °C at 50% relative humidity.

Table 2. High-grammage Paper Sheet-making Conditions According to Pulp Type and Beating Condition

Symbol	Beating Degree	Beating Condition	
	°SR	Disintegration Time (min)	Beating Time (min)
Hw-A-20°SR	20	20	3
Hw-A-30°SR	30		13
Hw-A-40°SR	40		19
Hw-B-20°SR	20		3
Hw-B-30°SR	30		15
Hw-B-40°SR	40		20
Hw-C-20°SR	20		3
Hw-C-30°SR	30		10
Hw-C-40°SR	40		17
Hw-D-20°SR	20		3
Hw-D-30°SR	30		12
Hw-D-40°SR	40		15
Sw-A-20°SR	20		3
Sw-A-30°SR	30		16
Sw-A-40°SR	40		22
Sw-B-20°SR	20		3
Sw-B-30°SR	30		18
Sw-B-40°SR	40		23

Table 3. High-grammage Paper Sheet-making Conditions According to Pulp Mixing Ratio

Symbol	Pulp Fiber Mixing Ratio	
	Hw-A-30°SR	Sw-A-30°SR
Control (Hw-A-30°SR)	100	-
Sw-10%		10
Sw-20%		20
Sw-30%		30

Evaluation of High-grammage Paper Properties

The mechanical properties (density, tensile strength, internal bond strength, and breaking length) of the high-grammage papers prepared under each condition were evaluated. The thickness was measured with a micrometer (L&W micrometer, Switzerland) to subsequently calculate the density. Tensile strength and breaking length were measured using a tensile tester (L&W tensile tester, Vaud, Switzerland).

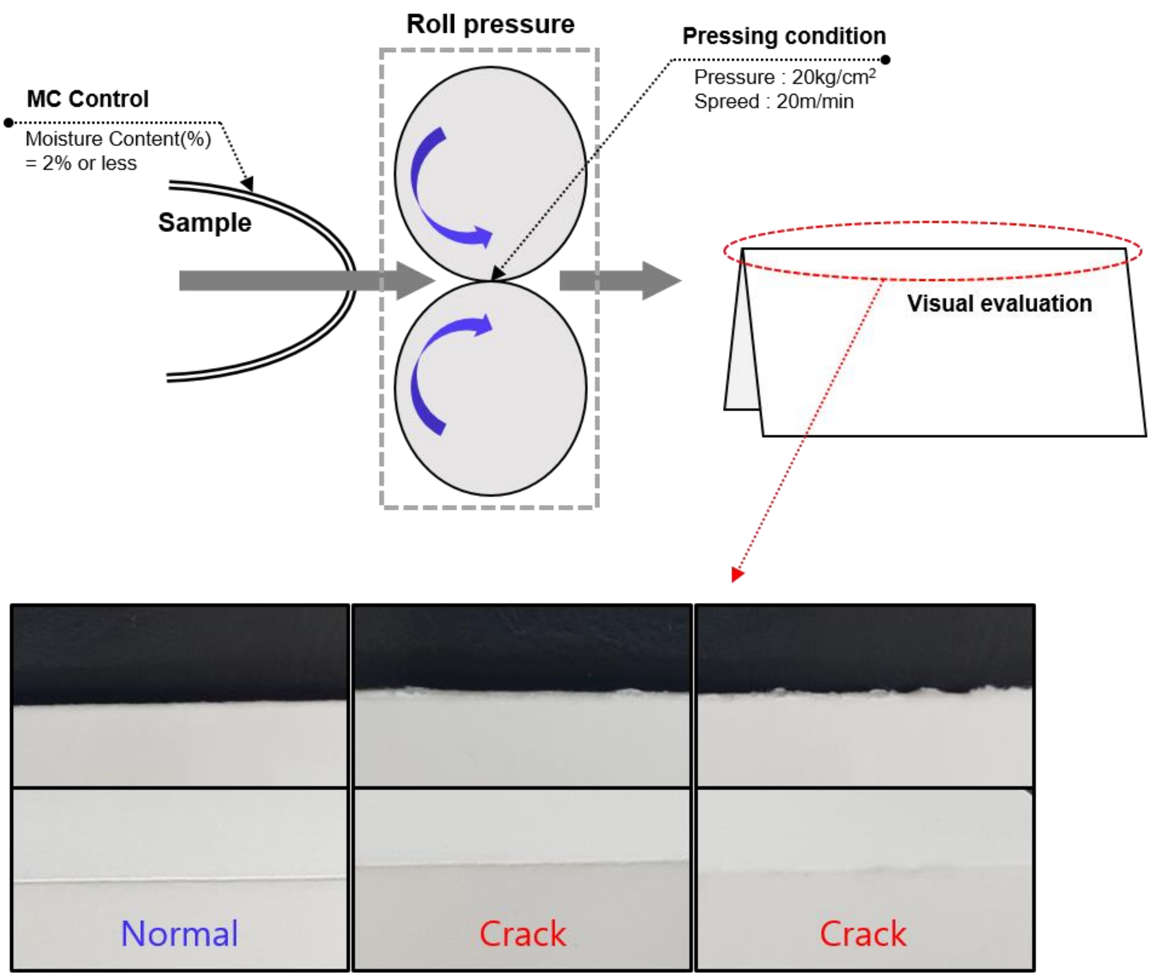

Fig. 1. Evaluation of fold cracking

Internal bonding strength was measured using a Scott bond tester (Z-direction tensile tester, Zwick Roell, Fürstenfeld, Austria) following TAPPI T541 om-21 (2021). To visually evaluate the correlation between mechanical properties and folding properties, each value was calculated as the proportional value of change within the range of maximum and minimum values, and comparative analysis was performed. The proportional value of change was calculated through the following Eq. 1,

$$R = \frac{D - V_{\min}}{V_{\max} - V_{\min}} \quad (1)$$

where R is the proportional value of change, D is the data value (density in g/m^3, tensile strength in kgf, internal bond strength in ft-Lb 1000, and breaking length in mm), $V_{\min}$ is the minimum value of the total data, and $V_{\max}$ is the maximum value of the total data.

Evaluation of Fold Cracking

Fold cracking was evaluated on a laboratory scale. To induce conditions susceptible to fold cracking, each sample was dried in an oven dryer at 135°C for 2 minutes to reduce the moisture content to below 2%. Subsequently, a roll press was used to apply linear pressure to the samples under consistent conditions of speed (20 m/min) and pressure (20 kg/cm^2) in order to simulate the harsh folding processing conditions. Thereafter, the degree of fold cracking was visually evaluated and classified as 'Normal' or 'Crack' (Fig. 1).

RESULTS AND DISCUSSION

Evaluation of Morphological Properties According to Pulp Fiber Types

Table 4 shows the morphological characteristics depending on the beating degree of six types of pulp. Considering hardwood pulp, as the beating degree was increased, the fiber length, width, and coarseness decreased, whereas the fiber fines increased. However, the fiber fines varied significantly depending on the type of pulp product, even with the same beating level. It was confirmed that the variations in fiber fines could be attributed to the differences in beating properties among the various types of pulp products, even when all products underwent the same level of beating. The fiber fines content of BCTMP was higher than that of BKP; pulp fibers composed of a single species, such as eucalyptus (Hw-A, B, C), exhibited fewer fiber fines than those in other samples (Hw-D). Softwood pulp also exhibited a similar tendency to that of hardwood pulp, and the fiber fines appeared differently depending on the species. In particular, the fiber length was noticeably decreased, and the fiber fines content was higher than that in hardwoods.

Correlation between Mechanical and Folding Properties of High-grammage Paper According to Pulp Fiber Type and Beating Degree

The proportional value of change of mechanical properties in line with the beating degree for each type of hardwood pulp are shown in Fig. 2. (Red line = crack, blue line = normal). All types of hardwood pulp demonstrated severe fold cracking at 20 °SR. In contrast, at 30 and 40 °SR, fold cracking was considerably reduced. The thickness was decreased approximately 41% from 508 to 302 µm, because the tensile stress attributed to folding was reduced, and the mechanical strength of the paper structure was improved. The breaking length was expected to decrease because of an increase in fiber fines by beating (Table 4). However, the overall mechanical properties increased with the increasing beating degree. In addition, Hw-A pulp, which had the lowest fiber fines, was confirmed to have improved the mechanical properties.

Table 4. Morphological and Folding Properties in Relation to the Beating Degree for Each Pulp Fiber

Symbol			Fiber Length	Width	Coarseness	Fiber Fines	Fold Cracking
			mm	µm	mg/m	%	
Hw	A	20 °SR	0.76	24.0	0.080	3.79	**Crack**
		30 °SR	0.68	24.0	0.078	6.72	Normal
		40 °SR	0.47	23.3	0.072	11.43	Normal
	B	20 °SR	0.75	24.0	0.100	4.85	**Crack**
		30 °SR	0.69	23.8	0.094	9.66	Normal
		40 °SR	0.43	23.5	0.091	17.45	Normal
	C	20 °SR	0.88	27.6	0.130	6.83	**Crack**
		30 °SR	0.65	27.2	0.127	10.45	Normal
		40 °SR	0.43	27.4	0.122	22.43	Normal
	D	20 °SR	0.68	19.5	0.090	8.27	**Crack**
		30 °SR	0.52	19.3	0.081	13.43	Normal
		40 °SR	0.32	18.1	0.074	30.27	Normal
Sw	A	20 °SR	2.81	31.5	0.191	4.33	Normal
		30 °SR	2.24	30.4	0.200	8.45	Normal
		40 °SR	1.88	28.9	0.188	16.47	**Crack**
	B	20 °SR	2.95	32.4	0.220	3.34	Normal
		30 °SR	2.16	33.6	0.230	11.60	**Crack**
		40 °SR	1.72	31.3	0.226	21.27	**Crack**

Softwood pulp showed the opposite results to those of hardwood pulp. The fold was satisfactory under low beating degree conditions (20 °SR), and fold cracking occurred under high beating degree conditions (30 and 40 °SR) (Fig. 3). As the beating degree increased, the internal bond strength, tensile strength, and density were increased, but the breaking length was slightly decreased or increased. The thickness decreased approximately 10% from 308 µm (20 °SR) to 278 µm (40 °SR), and the decrease in thickness because of beating was lower than that observed for hardwood pulp. As reported by Youn *et al*. (2012), a continuous increase in the mechanical strength deteriorated the folding properties. This is because the breaking length was not improved after beating, despite the high level of mechanical properties. Folding properties can be improved through the process of beating; however, it is crucial to apply it appropriately as it may negatively impact the economics of paper production, including decreased production speed, reduced wet-pressing efficiency, and increased energy requirements for drying.

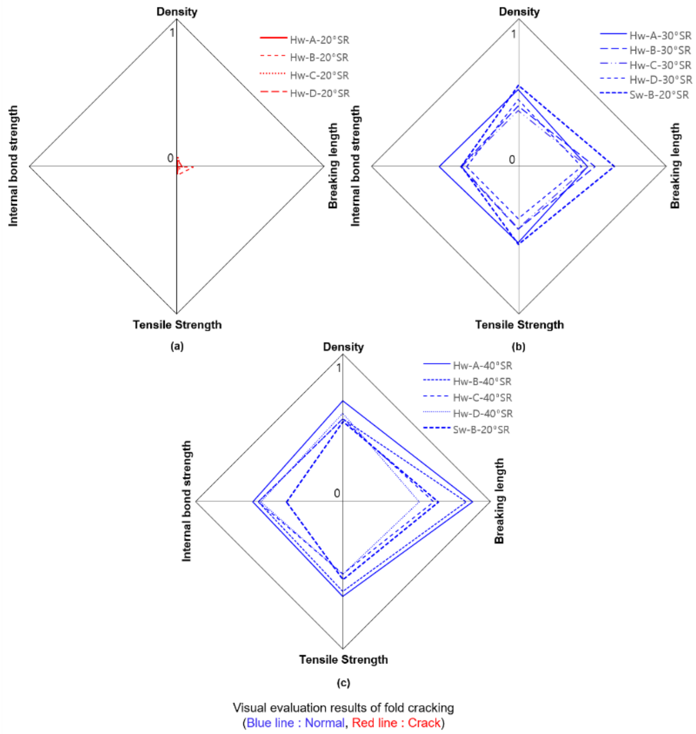

Fig. 2. Folding properties and proportional values of change of mechanical properties according to the increase in beating degree for different hardwood pulp fiber types (a: 20° SR; b: 30° SR; and c: 40° SR)

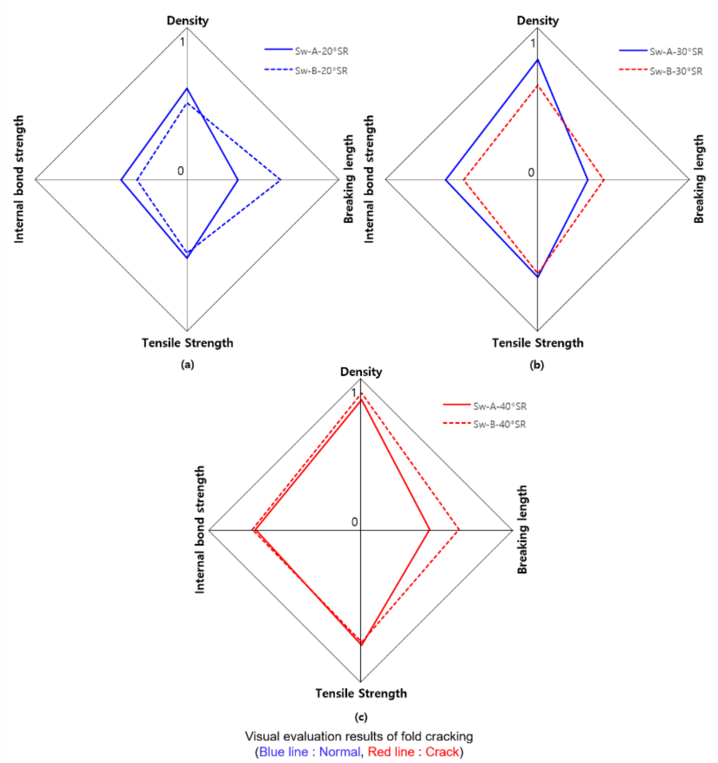

Fig. 3. Folding properties and proportional values of change of mechanical properties according to the increase in beating degree for different softwood pulp fiber types (a: 20 °SR; b: 30 °SR; and c: 40 °SR)

Correlation between Mechanical and Folding Properties of High-grammage Paper According to Mixing Ratios of Hw and Sw Pulps

The mechanical properties and folding properties of Hw-A and Sw-A pulps were compared based on the beating degree (Fig. 4). The breaking length of the hardwood pulp considerably increased, and the density, internal bond strength, and tensile strength were also increased. For softwood pulp, the density, internal bond strength, and tensile strength continuously increased, but the breaking length slightly changed.

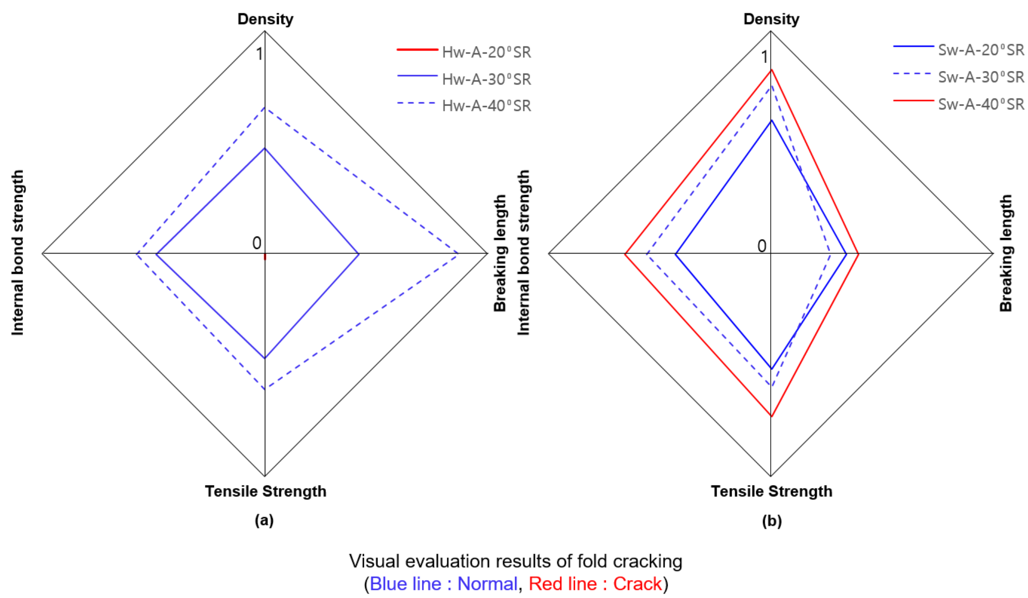

Fig. 4. Folding properties and proportional values of change of mechanical properties according to the beating degree of softwood and hardwood pulps (a: Hardwood pulp-A and b: Softwood pulp-B)

Based on these results, when 10%, 20%, and 30% of softwood pulp were mixed with 100% hardwood pulp, fold cracking did not occur under all conditions (Fig. 5). No apparent differences were observed in density, internal bond strength, and tensile strength; however, the breaking length tended to increase slightly when softwood pulp was added at 10% and 20%. However, when ≥ 30% of softwood pulp was added, the breaking length was decreased. Therefore, using ≤ 30% of softwood pulp effectively improved the folding properties. As previously reported in several studies (Youn *et al*. 2012), the inclusion of softwood fibers was expected to result in fold cracking. However, it was found that when the amount of softwood fibers added was less than 20%, fold cracking could be improved while breaking length was also enhanced. These outcomes are believed to be attributable to the high strength and flexibility of softwood fibers. To control the fold cracking while maintaining the inherent high bulk properties of high-grammage paper, mixing 10% to 20% of softwood pulp with hardwood pulp was the most effective method. Fold cracking can be reduced even under conditions of 100% hardwood pulp and 30 °SR (Control-Hw). However, this approach is expected to be utilized as an additional strategy for improving the breaking length in high-grammage paper exceeding 200 g/m^2.

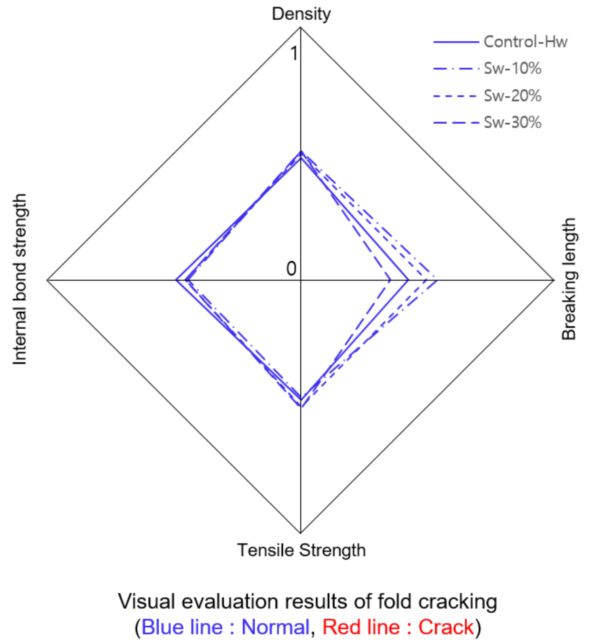

Fig. 5. Folding properties and proportional values of change of mechanical properties according to the mixing ratio of pulp fiber

CONCLUSIONS

In this study, to control the fold cracking of high-grammage paper that was not subjected to creasing, the mechanical and folding properties were evaluated based on the beating degree of six types of pulp fibers. The main conclusions are as follows:

1. The morphological characteristics of hardwood and softwood pulps changed with the beating degree, even when the same species and pulping method were considered. In particular, the fiber fines content varied based on the beating degree, and using pulp with low fiber fines content could effectively control fold cracking.
2. The mechanical properties of hardwood pulp were improved as the beating degree was increased; therefore, 30 °SR was found suitable. Softwood pulp had to be beaten below 30 °SR, because fold cracking occurred if the mechanical properties were increased beyond a certain level.
3. Mixing softwood pulp with hardwood pulp effectively reduced the fold cracking while maintaining the inherent high bulk properties of high-grammage paper.

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