

# Relationships Between the Changed Apparent Density of Recycled Handsheets and Their Mechanical and Physical Properties

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## ABSTRACT

Relationships between the changed apparent density of recycled handsheets and their mechanical and physical properties were demonstrated. Recycled handsheets with decreased apparent density possessed decreased mechanical properties such as folding endurance, modulus of elasticity, and tensile strength. Changes in the brightness and opacity of recycled handsheets were consistent with the effect of the changed apparent density of paper on its brightness and opacity due to beating and wet pressing. This was possibly because the decreased apparent density meant there were lots of air voids in the handsheet structure due to the loss in conformability and flexibility of less-swollen-recycled fibers as well as the lost mass of handsheets during recycling. The loss in swelling capability of wet fibers with recycling could be determined by light microscopy and the WRVs of the fibers. In this study, it seemed that handsheets produced from softwood bleached kraft pulp fibers could considerably retain some of their mechanical properties and opacity with good brightness when recycling not more than twice without additional chemical and mechanical treatments.

**Key words:** apparent density, recycled handsheets, mechanical properties, physical properties

## INTRODUCTION

Most of the mechanical and physical properties of paper can be affected by the recycling process. Mechanical pulp fibers give a denser and stronger paper sheet while chemical ones give a bulkier and weaker paper with recycling effects (Howard, 1990; Howard and Bichard, 1992). In the latter case, the bulkier and weaker paper sheet is possibly caused by a decrease in the strength of recycled paper due to the loss in the relative bonded area between fibers in their structure (Ellis and Sedlachek, 1993; Khantayanuwong, 2002).

Even though the effect of recycling treatments on the mechanical and optical

properties of recycled paper has been studied and usually reported in terms of changes in the properties with recycling times or with the freeness value of fibers (Horn, 1975; Bobalek and Chaturvedi, 1989; Howard, 1990; Howard and Bichard, 1992; Chatterjee *et al.*, 1993; Ellis and Sedlachek, 1993; Wistara and Young, 1999; Khantayanuwong, 2002; Khantayanuwong *et al.*, 2002;), it seems that few researches have demonstrated the effect of recycling treatment on those properties of recycled paper in terms of relationship to the changed apparent density of the paper (Cao *et al.*, 1998; 1999). Furthermore, it also seems that there is some doubt whether any research has emphasized how many times

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chemical pulp fibers can be recycled for papermaking while retaining considerable strength and good optical properties.

Therefore, it was the purpose of the present study to demonstrate the effect of recycling treatment on the mechanical and optical properties of recycled paper in terms of relationship to the changed apparent density. The recycling times at which chemical pulp fibers could be practically recycled for papermaking were also determined because recycled paper with considerable strength and good optical properties was very desirable in the industrial arena.

## MATERIALS AND METHODS

According to the standard methods of the Technical Association of Pulp and Paper Industries of the United States (TAPPI), a commercial bleached softwood kraft pulp was beaten to 300 ml of Canadian Standard Freeness by using a PFI mill (PFI mill No 266, Hamjern Hamar, Norway) and then was made into never-recycled handsheets (R0). All of the R0-handsheets were conditioned at  $23 \pm 1^\circ\text{C}$  with  $50 \pm 2\%$  relative humidity in a conditioning room for a week before systematically recycling samples following the recycling treatment suggested by Howard and Bichard (1992), i.e. they were randomly selected and were subject to submersion and re-disintegration in de-ionized water for handsheet-making to produce recycled-once-handsheets (R1) without additional pulp fibers for compensating weight loss. Some of the conditioned R1-handsheets were randomly selected and recycled one, two, or three times with the same treatment for producing R2-, R3-, and R4-handsheets, respectively. In this study, there were no additional chemical and mechanical treatments during production of the recycled handsheets. The weight loss of handsheets was determined with each recycling. The water retention value (WRV) of the pulp fibers re-disintegrated from the never-recycled and recycled handsheets was also

investigated by using a centrifugal method. The morphological aspects of the re-disintegrated fibers were ascertained with light microscopy (Olympus BX-50, Olympus Co., Japan). The apparent density of the conditioned never-recycled and recycled handsheets was ascertained before subjecting all of them to mechanical and physical tests for determining brightness, opacity, folding endurance, modulus of elasticity, tearing resistance, and tensile strength in the conditioning room by using a reflectometer (Automatic Reflectometer Model-3, Kumagai Riki Kogyo, Co., Ltd., Japan), a folding tester (Kumagai Riki Kogyo Co., Ltd, Japan), a tearing tester (Lorentzen and Wettress, Sweden), and a universal tensile testing machine (EJA-series, Thwing-Albert Co., USA), following the TAPPI standard methods.

## RESULTS AND DISCUSSION

Table 1 shows changes in the mechanical and physical properties of handsheets and pulp fibers due to the recycling treatment. The opacity of handsheets initially increased when recycled once and then started to decrease continually with the followed recycling times, even though the increase in brightness of recycled handsheets was clearly demonstrated. As can also be seen, there were decreases in the apparent density, folding endurance, modulus of elasticity, and tensile index of handsheets while the change in tear index of them followed the same pattern as the change in the opacity. The WRVs of pulp fibers re-disintegrated from the never-recycled and recycled handsheets decreased with the recycling treatment. The weight loss of handsheets during recycling is also demonstrated in Table 1. The percentages of weight loss were high when handsheets were recycled once or twice.

Relationships between the changed apparent density and the brightness and opacity of recycled handsheets are presented in Figure 1. As can be seen, changes in the apparent density of recycled handsheets also influenced their

brightness and opacity. The brightness of recycled handsheets prominently increased with the recycling treatment while their apparent density decreased. This was possibly because cellulose, which was a major component of the fiber wall of bleached chemical pulp fibers, was transparent, and the difference between the refractive index of cellulose and that of air voids in handsheet structure comprehensively pronounced the refraction and scattering of the light traveling throughout the structure. The brightness of handsheets demonstrates the amount of diffusely reflected light caused by the refraction and scattering (Casey, 1961b). Therefore, there possibly was an increase in the air voids in the structure of recycled handsheets which strongly increased the brightness itself. Nevertheless, the changed opacity of recycled handsheets was not consistent with their changed brightness. Eventhough Bobalek and Chaturvedi (1989) demonstrated that the opacity of recycled handsheets was not affected by recycling treatment, the opacity in this study initially increased and then decreased with the recycling treatment, i.e. the opacity of R1-handsheets was highest. As mentioned above, cellulose is a transparent material, therefore, handsheets with a very high apparent density seem to be transparent due to less air voids in their structure. This phenomenon could also occur in handsheets with a very low apparent density due to the transparency of air voids abundant in their structure. Both the changed brightness and opacity of recycled handsheets in this study were consistent with the effect of the changed apparent density of paper on its brightness and opacity due to beating and wet pressing (Casey, 1961b).

Figure 1 also shows relationships between the apparent density and the mechanical properties of handsheets affected by the recycling treatment. As can be seen, most of the mechanical properties of recycled handsheets such as folding endurance, modulus of elasticity, and tensile strength, fundamentally relied on their apparent

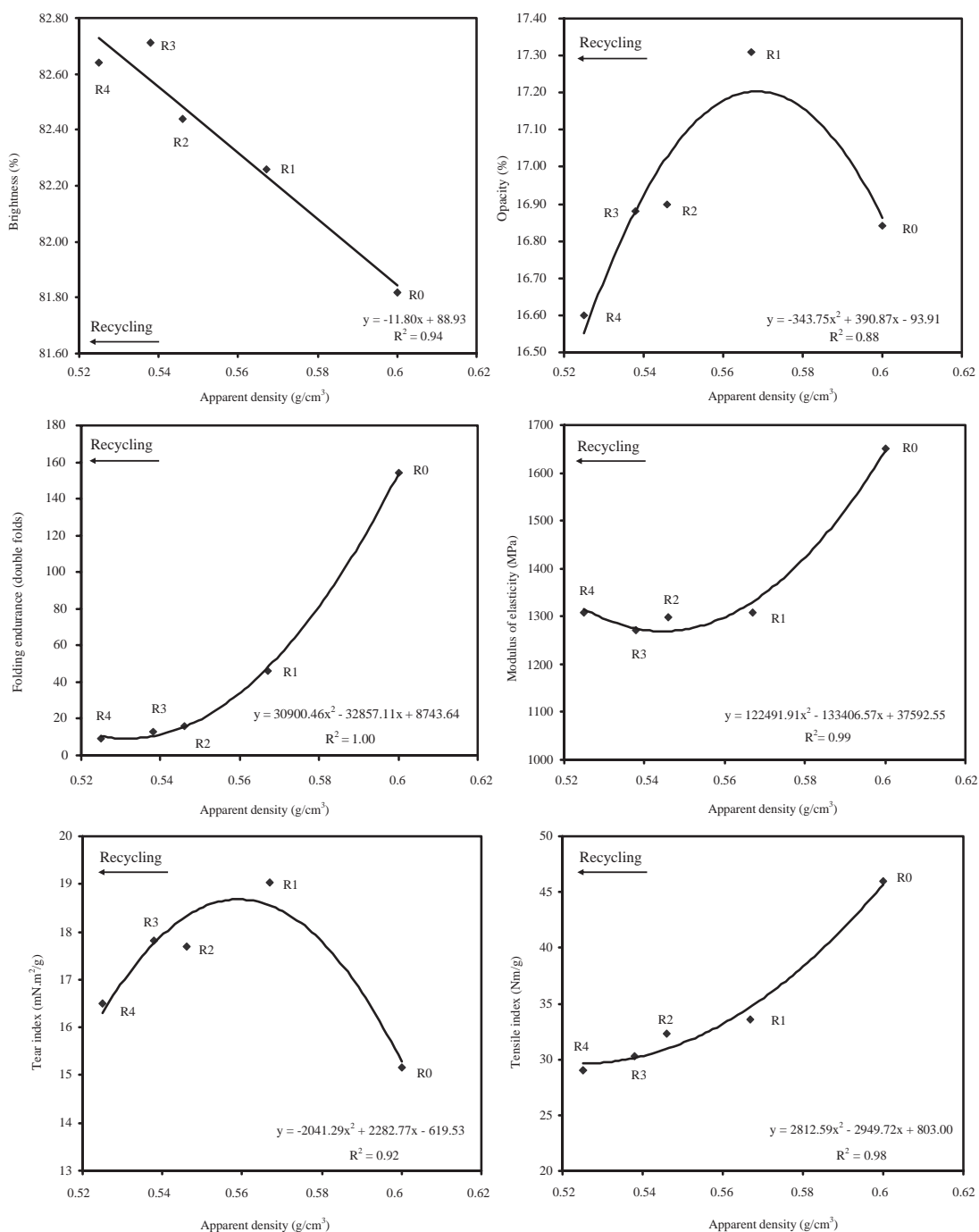
**Table 1** Recycling effect on mechanical and physical properties of handsheets and pulp fibers.

No of recycles	Apparent density (g/cm <sup>3</sup> )	Brightness (%)	Opacity (%)	Folding endurance (double folds)	Modulus of elasticity (MPa)	Tear index (mN.m <sup>2</sup> /g)	Tensile index (Nm/g)	WRV of pulp fibers produced from handsheets (g H <sub>2</sub> O/g O.D. pulp fibers)	Lost weight of handsheets during recycling (%)
R0	0.600±0.010	81.82±0.19	16.84±0.08	154±35	1650.53±121.47	15.171±0.286	45.956±1.477	1.01±0.03	-
R1	0.566±0.008	82.26±0.23	17.31±0.09	46±18	1308.33±83.84	19.030±0.229	33.553±2.365	1.09±0.07	1.993±0.224
R2	0.546±0.007	82.44±0.13	16.90±0.10	16±2	1298.79±59.82	17.703±2.223	32.252±1.121	1.08±0.14	2.544±0.552
R3	0.538±0.007	82.71±0.16	16.88±0.13	13±4	1271.66±114.82	17.824±1.123	30.285±2.048	0.89±0.03	0.797±0.026
R4	0.525±0.012	82.64±0.18	16.60±0.19	9±1	1306.89±125.94	16.490±1.304	29.052±0.713	0.83±0.15	0.565±0.018

N.B. 1. Each value is denoted at a range of 95 % confidence level.

2. R0, never-recycled handsheet; R1, recycled-once handsheet; R2, recycled-twice handsheet; R3, recycled-three-times handsheet; R4, recycled-four-times handsheet.

3. The WRV of beaten fibers was  $1.39 \pm 0.07$  (g H<sub>2</sub>O/g O.D. pulp fibers).



**Figure 1** Relationships between the apparent density and the mechanical and physical properties of handsheets.

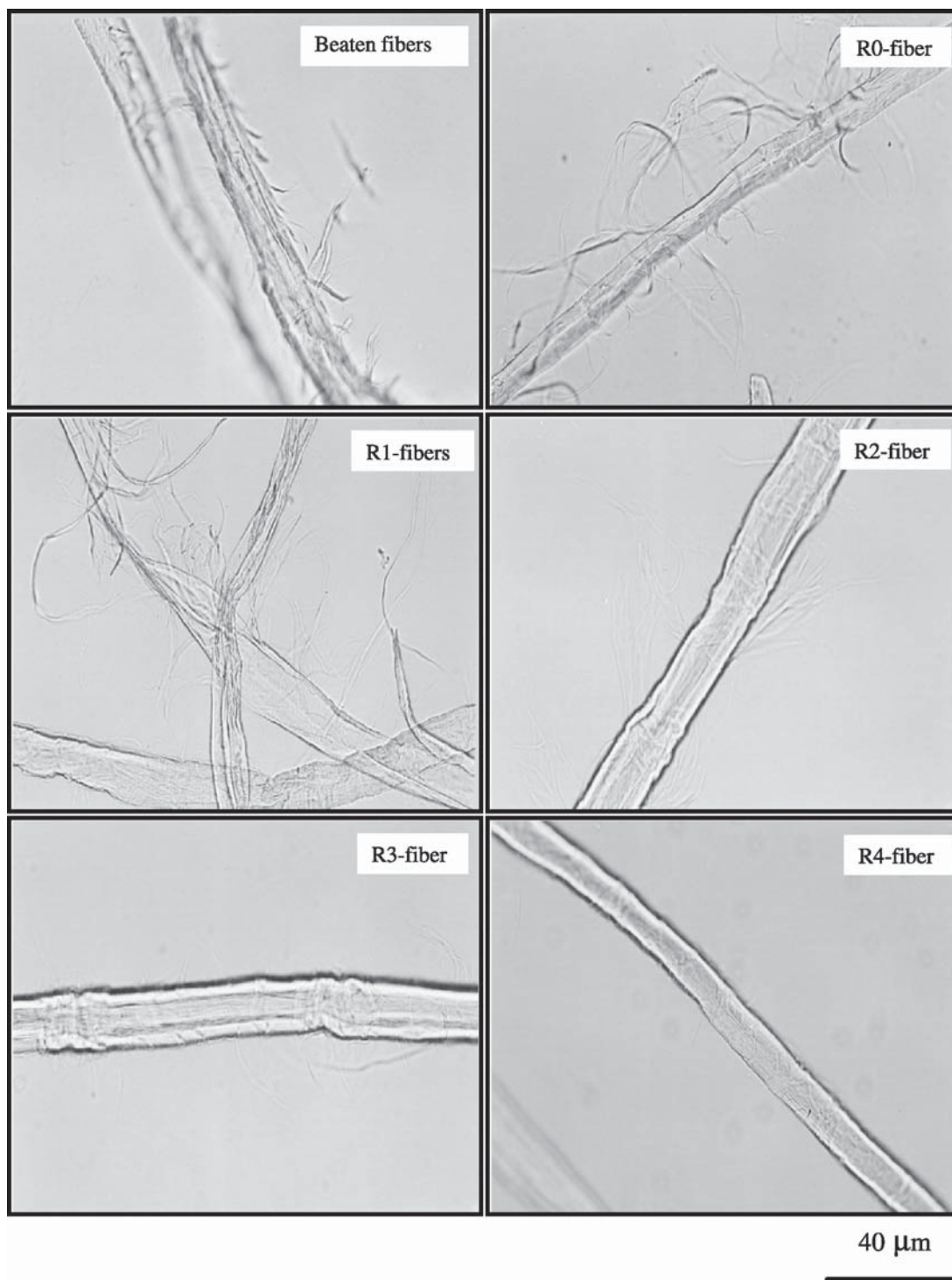
density, i.e. the decrease in their apparent density also decreased such mechanical properties. This was because paper strength depended on fiber strength and strength of interfiber bonding (Page, 1969). The decreased apparent density of recycled handsheets possibly meant there was an increased volume of air voids in their structure due to loss of good interfiber bonding area and the lost mass of recycled handsheets. Ellis and Sedlachek (1993) and Khantayanuwong (2002) demonstrated that the decrease in the tensile strength of recycled handsheets was solely affected by the loss in the interfiber bonding area in their structure because the specific interfiber bonding strength and fiber strength were not significantly affected at all. The lost interfiber bonding area with recycling treatment could be indirectly determined by a high correlation between the decreased apparent density and the increased light scattering coefficient of recycled handsheets.

As also can be seen in Figure 1, it seemed that the tearing resistance of recycled handsheets did not depend much on the decrease in their apparent density. The tearing resistance of handsheets tended to increase initially with the recycling treatment and then dramatically dropped. Nevertheless, the tearing resistance of recycled handsheets was still higher than that of never-recycled ones. Ackermann *et al.* (2000) pointed that a good runnability on paper machines with recycled fibers was possible because tear strength probably indicated the force required to pull out fibers at the tip of an advancing web rupture. Long fibers normally give a high tearing resistance to a sheet of paper due to the increase in the frictional drag work per fiber (Casey, 1961b).

During recycling, the portion of long fibers in handsheets probably increased due to fines loss. Fines are the broken fragments and the broken external fibrils of fiber walls that are able to pass through a 200 mesh wire screen (Retulainen *et al.*, 1998). Therefore, there was no doubt in this study that fines were lost during recycling because

a standard wire screen with 150 mesh was used for handsheet-making according to the TAPPI T-205 standard method. This phenomenon could be determined by the lost weight of handsheets as well as the loss in the external fibrils of fibers during recycling as demonstrated in Figure 2. The external fibrils were considerably lost when handsheets were recycled twice, i.e. the re-disintegrated fibers from R1-handsheets lost their external fibrils after being used for producing R2-handsheets or alternatively, the R2-fibers possessed fewer external fibrils than R1-fibers. This loss in the external fibrils of recycled fibers also directly corresponded to the lost weight of recycled handsheets and to their WRVs, e.g. the weight of recycled handsheets was reduced when recycled twice and the WRV of R1-fibers was highest due to having lots of the external fibrils as presented in Figure 2. As also can be seen in Table 1, the changed WRVs were consistent with the changed tearing resistance of handsheets due to recycling. This phenomenon could be used for explaining the initially increased and dramatically dropped of the tearing resistance because WRV was a parameter used to indirectly determine the swelling capability of wet fibers due to the water associated with them (Casey, 1961a). Wet fibers with a high WRV are good for swelling and are also flexible and conformable for consolidating a denser and stronger handsheet with good interfiber bonding areas. Khantayanuwong *et al.* (2002) showed microscopically that wet-swollen-fibers that were never recycled were more conformable for a good consolidated handsheet than recycled ones.

Therefore, according to the above results, it seemed that handsheets produced from beaten softwood bleached kraft pulp fibers could practically retain some of their mechanical properties and opacity with good brightness when recycling not more than twice without additional chemical and mechanical treatments.



**Figure 2** Loss in external fibrils of recycled fibers. N.B. R0, never-recycled handsheet; R1, recycled-once handsheet; R2, recycled-twice handsheet; R3, recycled-three-times handsheet; R4, recycled-four-times handsheet.



## CONCLUSIONS

Changes in the apparent density of handsheets during recycling were studied and demonstrated in terms of relationship to their mechanical and physical properties. As the apparent density decreased, most of the mechanical properties such as folding endurance, modulus of elasticity, and tensile strength also decreased. Relationship between the apparent density and the brightness and opacity of handsheets was consistent with the effect of the changed apparent density of paper on its brightness and opacity due to beating and wet pressing. This was possibly because the decrease in the apparent density meant there were lots of air voids in the handsheet structure due to the loss in the conformability and flexibility of less-swollen-recycled fibers and the lost mass of handsheets during recycling. The loss in swelling capability of wet fibers with recycling could be determined by the WRVs of the fibers and light microscopy. In this study, it seemed that handsheets produced from softwood bleached kraft pulp fibers could considerably retain their mechanical properties and opacity with good brightness when recycling not more than twice without additional chemical and mechanical treatments.

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