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Effects of Beating and Recycling on Strength of Pulp Fibers and Paper

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ABSTRACT

The effects of beating and recycling treatment on strength of pulp fibers and handsheets were ascertained in this study. The zero-span tensile strength of handsheets, which corresponds to strength of fibers as such, tended to increase by beating and recycling treatment. Therefore, the decrease in the tensile strength of recycled handsheets was caused by the decrease of interfiber bonding strength as explainable by using the Page equation. Because the recycling treatment did not affect the specific strength of interfiber bonding, the decreased strength of interfiber bonding solely stemmed from the decreased interfiber-bonded area.

Key words: beating, recycling, the Page equation, zero-span tensile strength

INTRODUCTION

The Page equation (Page, 1969) gives the relationship among the tensile strength of paper sheet, fiber properties, and interfiber bonding properties as follows:

$$\frac{1}{T} = \frac{9}{8Z} + \frac{12A\rho g}{bPL(RBA)}$$

where T = tensile strength of paper sheet, Z = zero-span tensile strength of paper sheet, A = fiber cross-sectional area, ρ = density of fiber wall, g = acceleration due to gravity, b = bond shear strength per unit bonded area (specific strength of interfiber bonding), P = perimeter of the fiber cross section, L = fiber length, and

$$\text{RBA} = \text{relative bonding area} = \frac{(S_0 - S)}{S_0}$$

where S_0 = light-scattering coefficient of the paper sheet in the absence of bonding between fibers, and S = light-scattering coefficient of the paper sheet in the presence of bonding between fibers.

In the case of low-yield or chemical pulp fibers, recycling treatment contributes to the decrease in apparent density and tensile strength of the paper made from them (Howard and Bichard, 1992). This is possibly caused by the decrease of fibers strength and/or the decrease in strength of interfiber bonding due to recycling effects. However, the effects of recycling treatment on strength of fibers and of interfiber bonding are still controversial. Some experts pointed out that there was no change in strength of fibers due to recycling treatment (Chatterjee *et al*., 1993; Howard, 1995). On the other hand, others demonstrated that recycling treatment could deteriorate strength of beaten chemical or low-yield pulp fibers whereas it increased strength of mechanical and thermomechanical or high-yield pulp fibers (Alanko *et al*., 1995; Bobalek *et al*., 1989). Determination of fibers strength is generally conducted by applying the zero-span tensile testing method to pieces of

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paper (Brandon, 1980).

Even though the specific strength of interfiber bonding and interfiber bonding area are two major factors influencing strength of interfiber bonding because the values of A, ρ, g, P, L and S_0 parameter in the Page equation are suggested to be constant, during recycling, the loss in bonded area at interfiber crossing sites is suggested as a major role of the decrease in strength of interfiber bonding (Howard, 1995; Page, 1969). This phenomenon certainly decreases the tensile strength of recycled paper if fibers strength is increased or is not affected by recycling treatment (Howard, 1995). Cao *et al.* (1999) confirmed that there was no change in the specific strength of interfiber bonding due to recycling treatment. Ellis and Sedlachek (1993) also found that the decreased tensile strength of recycled paper was the sole result of poor development of bonded area at interfiber crossing sites. However, recently, Gurnagul *et al.* (2001) demonstrated that the primary cause of tensile strength reduction upon drying was the loss of interfiber bonding strength, with a minor reduction caused by a loss in interfiber bonded area.

Therefore, it is the purpose of the present study to demonstrate the effect of beating history of fibers on changes in their strength induced by recycling treatment. The change in the specific strength of interfiber bonding, due to drying-and-rewetting cycles during recycling, is also ascertained in this study.

MATERIALS AND MATHODS

A virgin hardwood bleached kraft pulp (HBKP) was beaten for 2,500 and 7,500 revolutions (rev.) in a PFI mill. Both of the beaten HBKPs were subjected to making handsheets separately, according to TAPPI test methods. Some of the handsheets were separately soaked in de-ionized water for 24 hours before disintegration for making their own handsheets-R1 (recycled once). This procedure is named as "recycling treatment" hereafter. The recycling treatment was repeated for two more times to produce handsheets-R2 and -R3 from some of the handsheets-R1, respectively. An unbeaten virgin HBKP was also used for making its own handsheets and recycled ones including handsheets-R1, -R2, and -R3 by the same method. Every handsheet was conditioned at 23 °C with 50 % relative humidity following Japanese Industrial Standards (JIS) for a month. The conditioned handsheets were subjected to mechanical tests, following TAPPI test methods, for determining their 100 mm span and zero-span tensile indices. Their light-scattering coefficients were also ascertained by using a spectrophotometer (TOPSCAN TC-1800, Tokyo Denshoku Co., Ltd, Japan).

RESULTS AND DISCUSSION

Figure 1 shows the tensile indices of handsheets were decreased by the recycling treatment. As can be seen, the decrease in the tensile strength of recycled handsheets was substantially affected by the beating history of fibers, i.e., the recycled handsheets made from heavily beaten fibers (beaten for 7,500 rev.) lost their tensile strength more remarkable than those made from mildly beaten (beaten for 2,500 rev.) and unbeaten ones. Particularly prominent was the tensile strength of handsheets immediately dropped extensively at the first time of recycling. Because the tensile strength of a sheet of paper depends on both the strength of fibers (or zero-span tensile strength) and of interfiber bonding in the sheet according to the Page equation (Page, 1969), the decrease in the tensile indices of recycled handsheets seemed to rely on the decrease in strength of recycled fibers and/or the decrease in strength of interfiber bonding due to the recycling treatment.

Figure 2 demonstrates changes in the zero-span tensile strength of handsheets, which correspond to changes in strength of fibers, due to the recycling treatment. As can be seen, the zero-

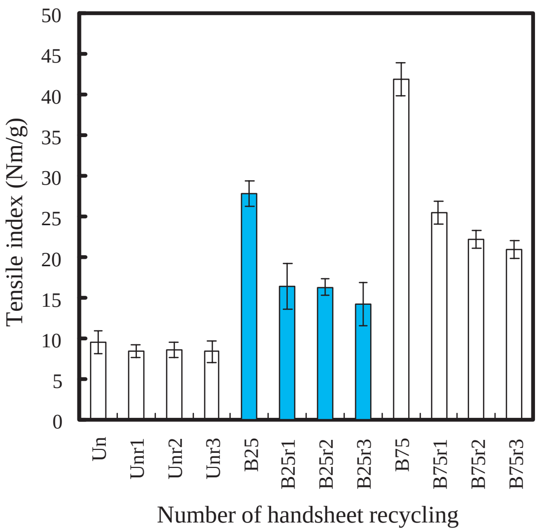

Figure 1 Changes in tensile indices of handsheets by recycling treatment. A pair of bars denotes a rage of 95 % confidence level. N.B. Un, unbeaten; B25, beaten for 2,500 rev.; B75, beaten for 7,500 rev.; r1, recycled once; r2, recycled twice; r3, recycled for three times.

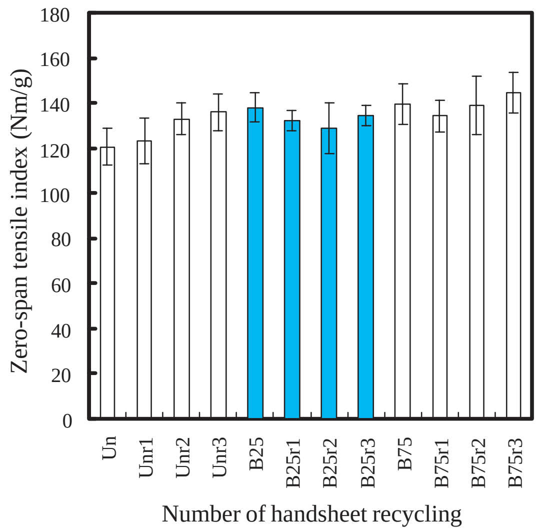

Figure 2 Changes in zero-span tensile indices of handsheets by recycling treatment. A pair of bars denotes a rage of 95 % confidence level. N.B. Un, unbeaten; B25, beaten for 2,500 rev.; B75, beaten for 7,500 rev.; r1, recycled once; r2, recycled twice; r3, recycled for three times.

span tensile strength of handsheets was slightly increased by beating treatment, i.e., both of the heavily and mildly beaten fibers were slightly stronger than the unbeaten ones. The zero-span tensile strength of the handsheets made from the unbeaten fibers was gradually increased continuously by the recycling treatment. Furthermore, the zero-span tensile strength of the handsheets made from the heavily beaten fibers also tended to increase when they were recycled for a few times. These phenomena could be explained by using the model suggested by Weise and Paulapuro (1996) that is shown in Figure 3. Delaminated parts of fiber wall structure, which were produced by the beating treatment, as well as cellulose microfibrils could possibly become attached together, by hydrogen bonds, during drying (Page and De Grace, 1967; Young, 1986). Some parts of the formed hydrogen bonds could not be

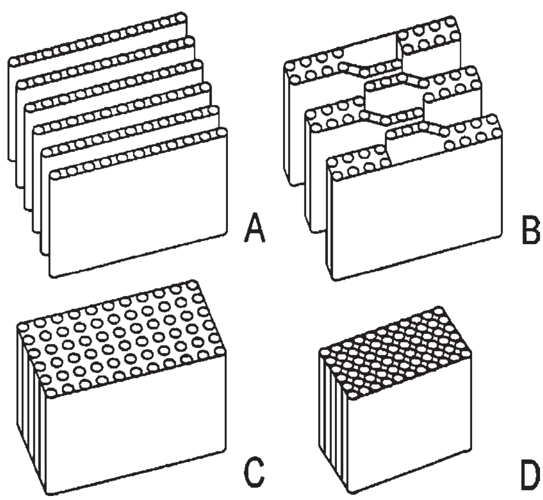

Figure 3 Delaminated parts of fiber wall structure could possibly become attached together (from A to D) by drying-and re-wetting cycles of recycling treatment (after Weise and Paulapuro, 1996).

disrupted by water molecules as is known as an irreversible form (Matsuda *et al*., 1994; Wiese and Paulapuro, 1996). Reorientation and alignment of the microfibrils are also expected to occur. Therefore, once-dried fibers with their tightly packed cell walls could be stiffer and more brittle, even in water, than never-dried ones. Khantayanuwong *et al*. (2001) confirmed that the drying treatment conducted with a high temperature condition could increase the elastic stiffness constant of fiber wall. Furthermore, as demonstrated in Figure 2, it possibly means that the cell wall of heavily beaten fibers could be tightly packed easier than that of mildly beaten ones due to its completely entire homogeneity of delaminated parts. As can be seen, the recycling treatment increased the zero-span tensile strength of the handsheets made from the heavily beaten fibers more remarkable than that of the handsheets made from the mildly beaten ones. However, the continuous increase in the zero-span tensile strength of the recycled handsheets made from the unbeaten fibers was possibly due to a very small amount of delaminated part of the original structure of fiber walls. The decrease in the re-swelling capability of dried or recycled fibers could be understandable by using the model of Weise and Paulapuro (1996) as well. As demonstrated in the research of Khantayanuwong *et al*. (2002b) and of Scallan and Tigerstrom (1992), the re-swelling capability of chemical pulp fibers was possibly decreased by the increase in irreversible hydrogen bonds and in crystallinity of fiber walls due to drying-and-rewetting cycles and recycling treatment. Furthermore, the re-opening capability of fiber lumens related to the re-swelling capability of single fibers in water also depends on the beating history of fibers. The decreased re-opening capability of fiber lumens is more remarkable in the case of dried beaten chemical pulp fibers than that of dried unbeaten ones (Ackermann *et al*., 2000).

Because none of the handsheets in this study was calendered, interfiber un-bonded area in the handsheets could be evaluated by means of the light-scattering property of handsheets, e.g. the value of light-scattering coefficient of a handsheet with a large interfiber un-bonded area is higher than that of the same kind of handsheet with a small one (Kurdin, 1980; Robison, 1980). Figure 4 shows changes in the light-scattering coefficients of handsheets affected by the recycling treatment. As can be seen, even though the increase in the light-scattering coefficient of recycled handsheets was not remarkable possibly due to recycling without using chemicals and heat treatment (Khantayanuwong *et al*., 2002a), the values of light scattering coefficient of the handsheets made from the unbeaten fibers are higher than those of the others made from the beaten ones. This means that the beaten fibers were more conformable, during handsheets making, than the unbeaten ones. The superior conformability of beaten fibers in a wet state, which is consistent with their swelling

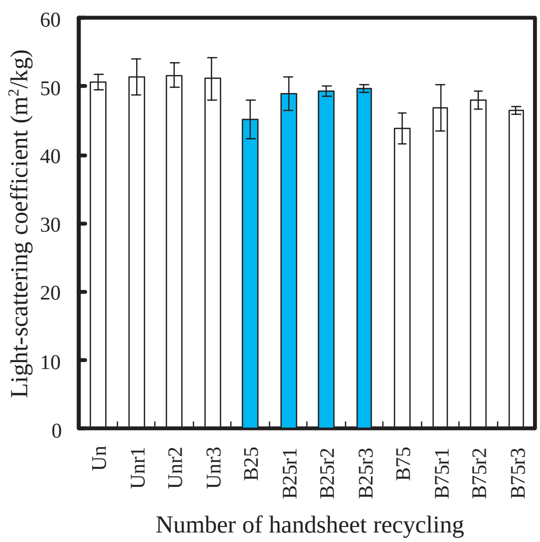

Figure 4 Changes in light-scattering coefficients of handsheets by recycling treatment. A pair of bars denotes a range of 95 % confidence level. N.B. Un, unbeaten; B25, beaten for 2,500 rev.; B75, beaten for 7,500 rev.; r1, recycled once; r2, recycled twice; r3, recycled for three times.

capability, could promote good interfiber contacts in handsheets in which interfiber un-bonded area in the handsheets is small spontaneously (Khantayanuwong *et al*., 2002a). Generally, more good interfiber contacts in handsheets, higher beating degree of fibers is necessary (Kurdin, 1980; Robison, 1980). Thus, the handsheets made from the beaten fibers were certainly stronger than those made from the unbeaten ones due to their larger interfiber bonded area and the slightly stronger cell wall of beaten fibers.

As shown in a lot of research, chemical pulp fibers lose their re-swelling capability due to drying and recycling treatment (Jang *et al*., 1995; Khantayanuwong *et al*., 2002a; 2002b; Scallan and Tigerstrom, 1992; Weise and Paulapuro, 1999). Recycled fibers losing their re-swelling capability also reduce conformability during handsheets forming (Khantayanuwong *et al*., 2002a). Therefore, in this study, the recycling treatment undoubtedly offered handsheets higher values of light-scattering coefficient, i.e., the un-bonded area in recycled handsheets was larger than that in their originated un-recycled ones. The increased values of the light-scattering coefficient of recycled handsheets were also consistent with the increasing tendency of zero-span tensile indices of them, as shown in Figures 2 and 4. This also possibly means that the recycled fibers in this study could not be conformed, due to their stiff and strong cell walls, for good interfiber contacts during handsheet forming.

As all the results mentioned above, it seems that the decrease in the tensile strength of recycled handsheets stemmed from the increased un-bonded area of them. This conclusion could be more credible if the specific strength of interfiber bonding was not affected by the recycling treatment, i.e., the decrease in strength of interfiber bonding might be due to the decrease in the specific strength of interfiber bonding and/or the increased un-bonded area. Cao *et al*. (1999) and Gurnagul *et al*. (2001) demonstrated the application of the modified Page equation to evaluate the change in the specific strength of interfiber bonding due to recycling and drying treatment. The modified Page equation is demonstrated as follows:

$$\left[\frac{1}{T}-\frac{9}{8Z}\right]^{-1}=\frac{b}{k}-\left[\frac{b}{kS_0}\right]S$$

where $\left[\frac{1}{T}-\frac{9}{8Z}\right]^{-1}$ = Page bonding strength, T = tensile strength of paper sheet, Z = zero-span tensile strength of paper sheet, b = bond shear strength per unit bonded area (specific strength of interfiber bonding), k = morphological aspects of fibers, S_0 = light-scattering coefficient of the sheet in the absence of bonding between fibers, and S = light-scattering coefficient of the sheet in the presence of bonding between fibers.

Because the morphological aspects of chemical pulp fibers are not affected by recycling treatment (Cao *et al*., 1999; Khantayanuwong *et al*., 2002a) and the S_0 value in this study is constant as a derived value from the relationship in Figure 5 at zero tensile strength (Robinson, 1980), the value of b/k, which is proportional to the specific strength of interfiber bonding, could be achieved by plotting the values in terms of the Page bonding strength of handsheets against their light-scattering coefficients (S). As can be seen in Figure 6, the relationship between the Page bonding strength and light-scattering coefficients of handsheets still gives a good linear correlation with a constant slope. The constant slope, which is the constant value of [b/kS_0] in the modified Page equation, means that there is no change in the specific strength of interfiber bonding by both the beating and recycling treatment. This result addresses the fact that the specific strength of interfiber bonding is constant and specific to such the kind of pulp fibers. Thus, the loss in the tensile strength of recycled handsheets only relied on the increase in interfiber un-bonded area. This phenomenon is consistent with the results demonstrated by Cao *et al*. (1999) and Ellis and Sedlachek (1993).

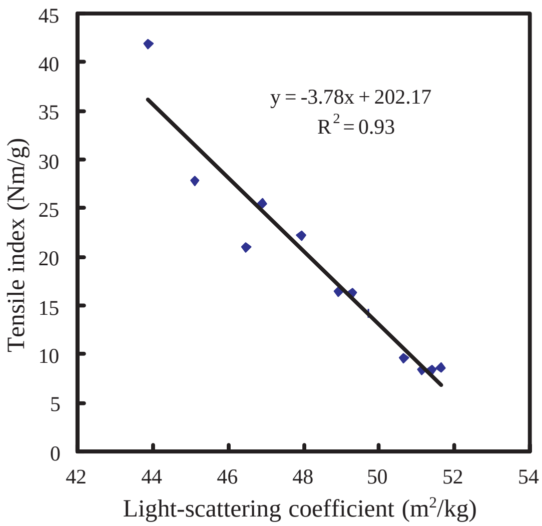

Figure 5 Relationship between light-scattering coefficient and tensile index of handsheets.

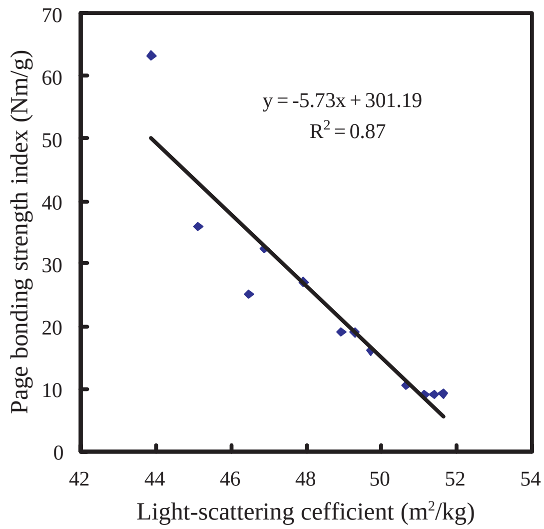

Figure 6 Relationship between Page bonding strength index and light-scattering coefficient of handsheets.

CONCLUSIONS

Because the zero-span tensile strength of handsheets, which corresponds to strength of fibers as such, tended to increase during recycling, the decrease in the tensile strength of recycled handsheets certainly stemmed from the lost strength of interfiber bonding. As demonstrated by using the modified Page equation, both the beating and recycling treatments did not affect the specific strength of interfiber bonding. Therefore, the lost strength of interfiber bonding, which also contributed to the decrease in the tensile strength of recycled handsheets, was substantially due to the decreased interfiber-bonded area.

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