Drewno 2017, Vol. 60, No. 200
DOI: 10.12841/wood.1644-3985.214.07

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CHEMICAL TREATMENT OF RECYCLED PULP FIBRES FOR PROPERTY DEVELOPMENT: PART 1. EFFECTS ON BLEACHED KRAFT PULPS

It was observed that sodium hydroxide, formamide, and ethyl acetate treatments enhance fibre swelling (re-swelling) abilities, especially after the first recycling stage. The highest water retention values (WRV) of 2.76 g/g were found at the second recycling stage of 7.5% formamide treatment (7.5Fa_2). However, the highest air permeability value of 8.83 m^2/sec. was found at the third recycling stage of 5.0% in ethyl acetate treated samples (5Et_3). The optical properties of the whiteness and brightness of the sheets presented a variation in the recycled sheets and with further recycling, usually resulted in marginal changes. The sodium hydroxide treatment usually resulted in a 1.2%–24.6% improvement of tensile strength. However, the highest burst strength improvement of 49.6% was achieved at a 7.5% NaOH charge at the first recycling stage (7.5Na_1). The formamide treatments resulted in approx. 5.3% to 53.2% tensile strength improvement. The highest burst of 4.48 kPa m^2/g was found at the first recycling stage of 7.5% (7.5Fa_1) conditions with formmaide, which indicates 88.2% higher than control (C_1). Moreover, the highest tensile (38.8%) and burst strength (87.8%) improvements were found in the ethyl acetate treatment at the first recycling stage of 7.5% chemical charge level, while the highest tear strength improvement (102.6%) was found at the second recycling stage of 7.5% treatment level. It was realised that increasing the ethyl acetate concentration is usually positively correlated with all three strength properties of the sheets.

Keywords: cellulose, recycling, chemical treatment, strengths, formamide, ethyl acetate

Introduction

Paper recycling has been practiced for more than 50 years. However, waste management and preservation of forest lands have become a worldwide problem. Hence, paper recycling has become an important issue for the pulp and paper industries. However, the main driving forces underlying the recycling action are not only environmental factors, but also economic pressures, which

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greatly promote paper recycling. The handling of municipal solid wastes (MSW) is a major problem in many countries. A number of choices can be utilized for solving municipal solid waste problems, such as preparing new landfill areas, conversion of MSW to energy, and reduction of the MSW through recycling [Cathie and Guest 1991; Patrick 1991].

However, it is generally well known that paper made from recycled fibres has inferior mechanical properties compared with those of virgin fibres. Important properties are dramatically reduced at certain levels from the first to the following cycles. This happens as a result of changes in the physicochemical properties of the fibres, (i.e., fibre strength, fibre length, fibre swelling capacity, and fibre bonding potential) [Biermann 1993; Scott and Abbott 1995].

Numerous studies have been conducted on the potential of paper making from recycled fibres. Most studies have shown that the mechanical properties of fibres are reduced upon recycling. Consistently, the decrease in property strength is caused by the drying effect on the fibres [Horn 1975; Howard and Bichard 1992; Brancato 2008]. However, one of the most important aspects of recycling is to understand how to increase and control the fibres' bonding potential. It is well documented that paper recycling, results in irreversible changes in the cellulosic bonding potential [Clark 1978; Bajpai 2014]. It is necessary to obtain a better understanding of the changes in recycled cellulosic fibres.

Several techniques could be used to enhance the strength properties of recycled fibres [Clark 1978; Wistara and Young 1999; Brancato 2008; Bajpai 2014]. However, treatments such as refining and chemical treatments can be used to recover the strength from loss up to a limited level. It has been suggested that the strength loss generally can be regained by refining to a certain level. Unfortunately, extensive or incorrect refining procedures limit the amount of strength that can be regained by refining [Clark 1978; Bajpai 2014]. Hence, the use of chemical additives during paper recycling without changing other pulping conditions could provide an alternative method for refining [Brancato 2008; Bajpai 2014]. Certain chemicals could be capable of facilitating hydrogen bonding and forming strong electrostatic bonds between fibres to interfibrous bonds [Wistara and Young 1999].

Wyk and Gerischer [1982] found that almost all strength properties of paper from unbleached sulphite pulp dramatically decreased up to the fourth cycle of recycling, after which the loss rate of strength properties considerably slowed down until the tenth cycle of recycling. McKee [1971] proposed that strength properties that are inversely related to fibre-fibre bonding, such as tear strength, were found to increase with the number of recycling cycles. Other researchers [Horn 1975; Wistara and Young 1999] also reported on the unusual effect of recycling on tear strength.

The formation of hydrogen bonds cross-linking between the cellulose microfibrils was extensively studied by Laivins and Scallan [1996] who proposed that, in delignified fibres, hydrogen bonds are formed between microfibrils upon drying, and that some of these additional hydrogen bonds are retained after re-wetting. Atalla [1992] hypothesized that the dehydration process carried out under conditions that promote molecular mobility can result in enhancing the order at secondary and tertiary levels of molecular organization. This effect, in most cases, produces a negative effect on recycled fibres.

Katz et al. [1981] proposed that the mechanism of fibre swelling involves differential concentration of ions within the gel and in the external aqueous phase, creates a differential osmotic pressure. A greater concentration of ions within the gel draws additional water that causes the cell wall to swell.

It is well known that fibres have a significant effect on the mechanical properties of sheets. However, the contribution of fibre bonding to strength development and fibre swelling in the formation of interfibrous bonds is a major effect. In contrast, recovered fibres have never recovered their original swollen dimensions, so they are not as flexible or conformable as before drying. Hence, without the proper swelling of fibres, the close contact with neighbouring fibre affects the tightly bonded crossings, and these effects, limit the strength of paper products [Clark 1978; Wistara and Young 1999; Brancato 2008; Bajpai 2014].

In this investigation, a basic approach was used to understand and improve the properties of recycled pulp with certain chemical treatments. Three different chemical treatments chosen in this study have been found to enhance the strength properties of pulp in certain levels to obtain recycled pulp with acceptable strength property.

Materials and methods

Commercially utilized, fully bleached softwood and hardwood Kraft pulp were supplied from a paper mill. The pulp was mixed according to typical mill use (40:60 hardwood/softwood pulp) and disintegrated in a laboratory-type blender as per standard procedure. The general characteristics of the pulp are given in table 1. The pulp was refined to PFI mill at the freeness of 400-450 ml (CSF). The refined pulp was made into hand sheets following TAPPI standard procedures.

The chemical treatments were utilized after the disintegration of pulp (recycling) and were designed to mainly increase the swelling capacity of the pulp and disrupt the cellulose paracrystalline regions through chemical modification.

The treatment of wood and cellulosic fibres with various chemicals has been a topic of research for many years. However, a well-stated approach developed to describe cellulose fibre swelling by organic liquids is that of Mantanis et al. [1994 and 1995], which classified organic liquids according to their hydrogen bonding potential (HBP) and cohesive energy density (CED). According to their

Table 1. The general characteristics of pulps

Property	Softwood pulp	Hardwood pulp
Fibre length (mm)	3.0-3.7	1.4-1.8
Fibre width (μm)	27-38	18-32
Fibre wall thickness (μm)	2.9-3.0	5.0
Fibre coarseness (μg/m)	160-200	130-200
Ash (%)	0.5	0.5
Alpha cellulose content	>91	>91
Degree of polymesization (DP)	900-1300	900-1300
Solubility (alkali)	<2.5	<2.5
Brightness (ISO; %)	>85	>80

approach, formamide is classified in Class I: high CED and high hydrogen bonding parameter (HBP); while ethyl acetate is classified in Class II: medium CED and high to medium HBP. Moreover, Stamm [1964] suggested that water and formamide have the percent swelling capacity of cellulose 100 and 123, respectively. Thus, ethyl acetate and formamide, as an organic solvent, and sodium hydroxide, as inorganic, being the most used chemicals in the paper industry, were selected for the chemical treatment of recycled fibres to study the effects on swelling and bonding (strength) of cellulose fibres during recycling. All chemicals were purchased by a chemical company with a purity of 99.9%, unless otherwise noted.

The fibres were reacted in each recycling stage in a closed container with three different levels of chemical concentration (5.0%, 7.5%, and 10%) based on oven-dried pulp. The chemical treatment of the pulp was conducted at a 0.5% consistency (typically used in paper manufacturing). The reaction was conducted at a temperature of 25°C (room temp.) for 12-16 hours. After treatment, the pulp was washed thoroughly with deionized water and beaten to obtain a freeness of about 400 ml (CSF).

The hand sheets for strength and physical properties were made in accordance with standard [TAPPI T205 om-88]. The strength properties also were determined in accordance with TAPPI standards. This involved the determination of tensile (TAPPI T494 om-96), burst (TAPPI T403), and tear strengths (TAPPI T414).

Three recycling stages were carried out in this study. Recycle 1 refers to the first-time repulping of recycled and dried fibres; recycle 2 refers to the repulping of dried fibre for the second time; and recycle 3 refers to the repulping of dried fibre for the third time.

Water retention value (WRV) was determined to measure the level of fibre swelling, based on centrifugation methods. The following condition for WRV determination is considered as standard [Wistara and Young 1999; Wistara et al.

1999]; a specially made pad of pulp is centrifuged for 15 minutes with the centrifugation force of 3000 G:

$$WRV = (WA – W B)/WA,$$

in which WA = the weight of the pulp before centrifugation (g); WB = the weight of the pulp after centrifugation (g).

The physical and optical properties of hand sheets were measured according to TAPPI T220 sp-96, ISO 2469 [2014], TAPPI T425 om-96, ASTM E313, and TAPPI T460 om-02, standard methods, respectively.

Results and discussion

Table 2 lists the comparison of physical and optical properties of paper produced from recycled fibres. It can be seen that the recycling usually affects the lower density of sheets. This is expected, considering the slightly fibrillated fibres (i.e., recycled), and could produce a relatively porous structure, which results in a lower sheet density. The results found for air permeability (table 2) also clearly support this information.

A number of researchers have already reported that the water retention value (WRV) could be useful for determining swelling properties of the fibres as well as the degree of hornification [Clark 1978; Wistara and Young 1999; Brancato 2008; Bajpai 2014]. The highest WRV values of 2.76 g/g were found at the second recycling stage of 7.5% formamide treatment ($7.5Fa_2$), whereas the lowest WRV values of 0.75 g/g were observed at the third recycling stage of control samples (C3). It appears that all three chemical treatments enhance fibre swelling (re-swelling) ability, especially after the first recycling stage. It was assumed that the chemicals reduced the surface tension and, as a result, promoted the penetration into the cell wall following the swelling of fibres to some extent. It already has been reported that, in a typical chemical treatment, the swelling of cellulose fibres takes place from the surface and amorphous region, thereby reducing the surface tension of the fibres and simultaneously creating new hydrogen bonding places [Horn 1975; Clark 1978; Brancato 2008; Wistara and Young 1999; Wistara et al. 1999]. However, it is also reported that there is a definite correlation between some chemical treatments (i.e., alkali, alcohol, amide, etc.) and the swelling properties of cellulose fibres. Those effects on crystallinity and orientation angle within the cellulose structure, especially in an amorphous region of further H-bonding place for liquids [Mantanis et al. 1994; 1995; Wistara and Young 1999; Wistara et al. 1999]. The results found in this study clearly contribute to these hypotheses.

It appears, however, that recycling has effects on increasing air resistance compared with control samples at a similar recycling stage. This result has also correlated with sheet density properties. The highest air permeability value of 8.83 m^2/sec. was found at the third recycling stage of 5.0% ethyl acetate treated samples ($5Et_3$).

Table 2. Physical and optical properties of chemical treated recycled pulps

Sample	Density (g/ cm^3)	WRV (g/g)	Air perm. (m^2/sec)	Whiteness index (%)	Brightness (%)	Opacity (%)
C_1	0.50	1.42	2.48	76.34	74.65	87.83
C_2	0.39	1,08	3.08	79.96	74.49	92.96
C_3	0.37	0.75	7.64	80.92	79.48	94.09
$5Na_1$	0.48	1.71	1.99	76.74	74.35	89.44
$5Na_2$	0.37	1.82	4.28	84.42	79.77	95.71
$5Na_3$	0.35	2.45	4.62	82.34	79.87	95.70
$7.5Na_1$	0.49	2.51	1.16	79,92	78.38	91.22
$7.5Na_2$	0.44	2.55	3.90	82.76	81.28	94.78
$7.5Na_3$	0.44	2.59	5.73	82.60	81.18	94.69
$10Na_1$	0.55	1.91	1.35	78.06	76.40	88.58
$10Na_2$	0.44	2.15	2.74	82.11	80.79	94.11
$10Na_3$	0.43	2.18	6.22	81.59	80.14	93.52
$5Fa_1$	0.55	1.81	2.09	75.92	73.65	88.17
$5Fa_2$	0.40	2.16	6,26	81.07	78.54	95.82
$5Fa_3$	0.37	2.12	3.45	81.24	78.75	95.37
$7.5Fa_1$	0.46	2.52	1.68	77.24	75.27	88.32
$7.5Fa_2$	0.42	2.76	2.18	78.81	77.04	91.39
$7.5Fa_3$	0.41	1.61	3.77	80.14	78.26	93.48
$10Fa_1$	0.44	2.21	2.59	75.72	73.91	86.24
$10Fa_2$	0.44	2.32	3.55	80.08	78.41	92.84
$10Fa_3$	0.44	1.83	3.60	78.30	76.61	90.92
$5Et_1$	0.44	1.89	1.58	77.48	75.75	88.50
$5Et_2$	0.44	1.99	2.45	80.47	79.36	92.87
$5Et_3$	0.39	2.65	8.83	78.42	77.13	91.12
$7.5Et_1$	0.50	2.01	2.47	75.64	73,48	86.05
$7.5Et_2$	0.46	2.22	2.61	78.52	78.84	90.67
$7.5Et_3$	0.38	2.66	6.14	78.32	76.57	90.67
$10Et_1$	0.48	1.91	1.54	76.09	74.36	86.06
$10Et_2$	0.45	1.97	2.67	78.73	76.96	90.99
$10Et_3$	0.44	2.79	3.28	78.13	76.95	90.54

C – control, 1-3 – recycling stage, Na – Sodium hydroxide; Fa – Formamide.; Et – Ethyl acetate; 5, 7.5, 10 – % chemical charge (based on oven dry pulp).

The optical properties of whiteness and brightness of the sheets presented a variation in the recycled sheets, with further recycling usually resulting in marginal changes. The highest whiteness value was found to be 84.42% ($5Na_2$), which indicates 5.3% improvement according to the control (C_2). The highest brightness values were also found at the second recycling stage of 7.5% sodium hydroxide treatment conditions (7.5Na_2), which indicated approximately a 9.1% brightness increase than that of the control (C_2). However, marginally the same or reduced brightness and whiteness values were observed for formamide and ethyl acetate treatments. The more or less similar results were also found in the opacity properties of sheets.

The comparative mechanical strength properties of sheets made from recycled fibres with statistical results are given in table 3. Numerous studies have shown that recycling effects are not only the physical and optical properties but also the mechanical strength properties [Bhat et al. 1991; Ellis and Sedlachek 1993; Gurnagul 1995]. Similar results are found in this study for untreated fibres. Typically, all three strength properties of the sheets decrease at a certain level as the recycling stages continue. However, the chemical treatment during recycling led to relatively higher sheet strength properties than control samples at a similar recycling stage. In general, all three chemicals had effects on improving or stopping the decrease effects on the strength of sheets at some level.

For sodium hydroxide treatment, except for the first recycling stage of 5.0% (5Na_1) and the third recycling stage of 7.5% (7.5Na_3) and 10.0% (10Na_3), which show a lower level of tensile strengths, all other sodium hydroxide treatments resulted in a 1.2%-24.6% improvement. Similar results were also found for burst strength, in that the highest improvement of 49.6% was achieved at 7.5% NaOH charge at the first recycling stage (7.5Na_1). In contrast, this condition gave a tear strength of 2.56 Nm^2/g, which indicates a -12.6% lower result, according to the control (C_1). In all other conditions, tear strength was improved 9.6% to 28.3%.

For formamide treatment, except for the third recycling stage of 10.0% (10Fa_3), which shows -5.2% lower tensile strength, all other formamide treatment conditions demonstrated an approx. 5.3% to 53.2% improvement. However, it is important to note that all formamide treatments positively affect burst strength. The highest burst of 4.48 kPa m^2/g was found at the first recycling stage of 7.5% (7.5Fa_1) condition, which indicates an 88.2% higher level than the control (C_1). Interestingly, at the first recycling stages of three concentration levels, the tear strengths of sheets decrease at -3.9% (5Fa_1), -27.6% (7.5Fa_1), and -13.3% (10Fa_1), respectively. But at the second and third recycling stage, some improvement of tear strengths was observed with formamide.

For ethyl acetate treatment, except for the 5.0% level, all ethyl acetate conditions demonstrated considerable improvement of all strength properties. However, the highest tensile (38.8%) and burst strength (87.8%) improvements were found at the first recycling stage of 7.5% treatment level, while the highest tear strength improvement (102.6%) was found at the second recycling stage at

Table 3. Strength properties of chemical treated recycled pulps

Trt.	Tensile strength (Nm/g)	Change accor. to (C_{1-3}, %)	Burst strength (kPa m^2/g)	Change accor. to (C_{1-3}, %)	Tear strength (Nm^2/g)	Change accor. to (C_{1-3}, %)
C_1	37.57	0	2.38	0	2.93	0
C_2	30.54	0	2.30	0	1.84	0
C_3	28.20	0	2.16	0	1.77	0
$5Na_1$	33.01	-12.1	2,48	4.2	2.60	-0.11
$5Na_2$	30.90	1.2	2.17	-5.6	2.36	28.3
$5Na_3$	28.17	-0.01	1.96	-9.3	2.06	16.5
$7.5Na_1$	46.82	24.6	3.56	49.6	2.56	-12.6
$7.5Na_2$	35.16	15.1	2.35	2.2	2.06	11.9
$7.5Na_3$	26.78	-5.1	1.74	-19.4	2.21	24.8
$10Na_1$	39.66	5.6	3.09	29.8	3.21	9.6
$10Na_2$	33.69	0.3	2.64	14.8	2.20	19.6
$10Na_3$	24.75	-12.2	1.95	-9.8	2.08	17.5
$5Fa_1$	39.55	5.3	3.55	49.1	2.52	-13.9
$5Fa_2$	41.93	37.3	3.26	41.7	1.48	-19.6
$5Fa_3$	36.63	29.9	2.85	32.8	1.90	7.3
$7.5Fa_1$	53.52	42.5	4.48	88.2	2.12	-27.6
$7.5Fa_2$	46.80	53.2	3.54	53.9	2.04	10.9
$7.5Fa_3$	39.41	39.8	2.88	33.3	2.03	14.7
$10Fa_1$	45.76	21.7	3.67	54.2	2.54	-13.3
$10Fa_2$	42.01	37.6	3.23	40.4	2.12	12.2
$10Fa_3$	26.79	-5.0	2.47	14.3	3.67	107.3
$5Et_1$	45.25	20.4	3.13	31.5	2.71	-7.5
$5Et_2$	28.34	-7.2	2.16	-6.1	2.36	24.9
$5Et_3$	17.38	-38.4	1.42	-34.3	0.93	-47.4
$7.5Et_1$	52.16	38.8	4.47	87.8	4.66	59.1
$7.5Et_2$	40.92	33.9	3.08	33.9	3.83	102.6
$7.5Et_3$	36.21	28.4	2.76	27.8	3.20	80.8
$10Et_1$	48.60	29.4	4.15	74.3	4.35	48.6
$10Et_2$	34.75	13.8	2.78	20.9	3.22	70.4
$10Et_3$	35.27	25.1	2.87	32.9	2.58	45.8

C – control, 1-3 – recycling stage, Na – Sodium hydroxide; Fa – Formamide.; Et – Ethyl acetate; 5, 7.5, 10 – % chemical charge (based on oven dry pulp).

a 7.5% treatment level. It was realized that increasing the ethyl acetate concentration is usually positively correlated with all three strength properties of sheets.

It already has been well established that physical properties of fibres as well as their ability to swell and bond potential are typically diminished during recycling. Especially, the reduction in fibre flexibility with lower lengths after drying reduces the strength potential of recovered fibres [Bhat et al. 1991].

During the drying of chemical pulp, hydrogen bonds are formed between the cellulose chains in the cell wall, and some of these bonds remain unbroken on re-wetting. Hornification reduces interfibre bonding, which typically reduces the paper's density, tensile, and burst strength [Howard and Bichard 1992; Minor 1994; Brancato 2008; Bajpai 2014]. All these literature findings and suggestions are consistent with our untreated pulp's results. However, the paper strength is a consequence of many different interactions. Therefore, attributing the strength loss or gain to a single factor might be an oversimplification of the whole issue. Moreover, it is reasonable to suggest that the loss in paper strength could be restored by increasing the surface bonding agents of the fibres at certain levels. Hence, the swelling of cellulose fibres with selected chemicals may directly affect the properties and stretch ability of the sheets that are closely related to burst and tensile strengths. High stretch papers usually have high tensile and burst strength compared with low stretch pulps at the same comparison level. Furthermore, the bonding of fibres depends on the hydrophilic nature of the fibre surface and, consequently, on the ability to form hydrogen bonds. This is favoured by creating an additional surface area (contact area) inside the microfibers, thus affecting further interfibre bonding and, as a result, producing sheets that have increased strength. In contrast, tear strength is fairly complicated and depends on cell wall properties (thickness, fibrillation level, etc.). It has already been reported that paper with high burst and tensile strength could produce lower tear strength or vice versa [Wistara and Young 1999; Wistara et al. 1999]. In our study, we found similar results for formamide and ethyl acetate treated sheets.

Figures 1-3 show the sodium hydroxide, formamide, and ethyl acetate effects with recycling number on tensile (fig. 1), burst (fig. 2), and tear strength (fig. 3) properties of sheets, respectively.

The dependence of tensile strength to recycling numbers as a function of chemical charge shows that tensile strength has a directly proportional dependence on both parameters (fig. 1). The tensile strength of paper is usually used as an indication of the treatment effects on the paper strength derived from factors such as fibre strength and bonding. All treatment conditions apparently bring about an effect of improved strength for paper. It also was observed that, up to a 7.5% chemical charge, there is a level of improvement; beyond this level (10%), there is decreasing tendency observed for all three chemical treatments of recycled fibres. This suggests that tensile strength development or improvement is possible at optimum treatment conditions (5.0 and 7.5% chemical charge); beyond this level, lowered tensile strength was observed. Hence the different mechanisms should control the increase or decrease in tensile strengths. This is probably due to either optimum roughening or loosening of the fibres (fibrillation) at suitable conditions or elastic limits of fibre swelling at those points. Hence, fibrillation and swelling increases fibre surface areas and exposes cellular components that are important for inter-fibre bonding.

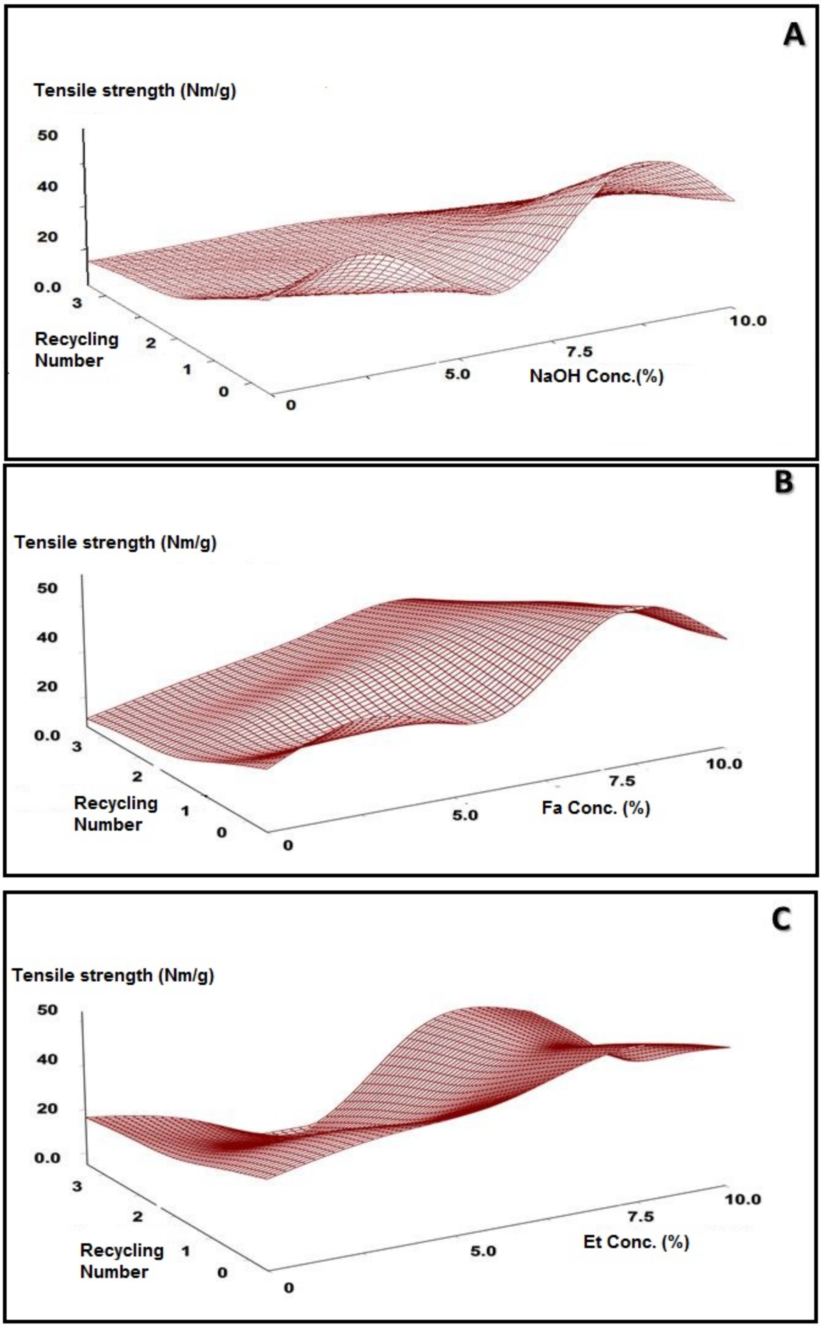

Fig. 1. Tensile strength of recycled papers

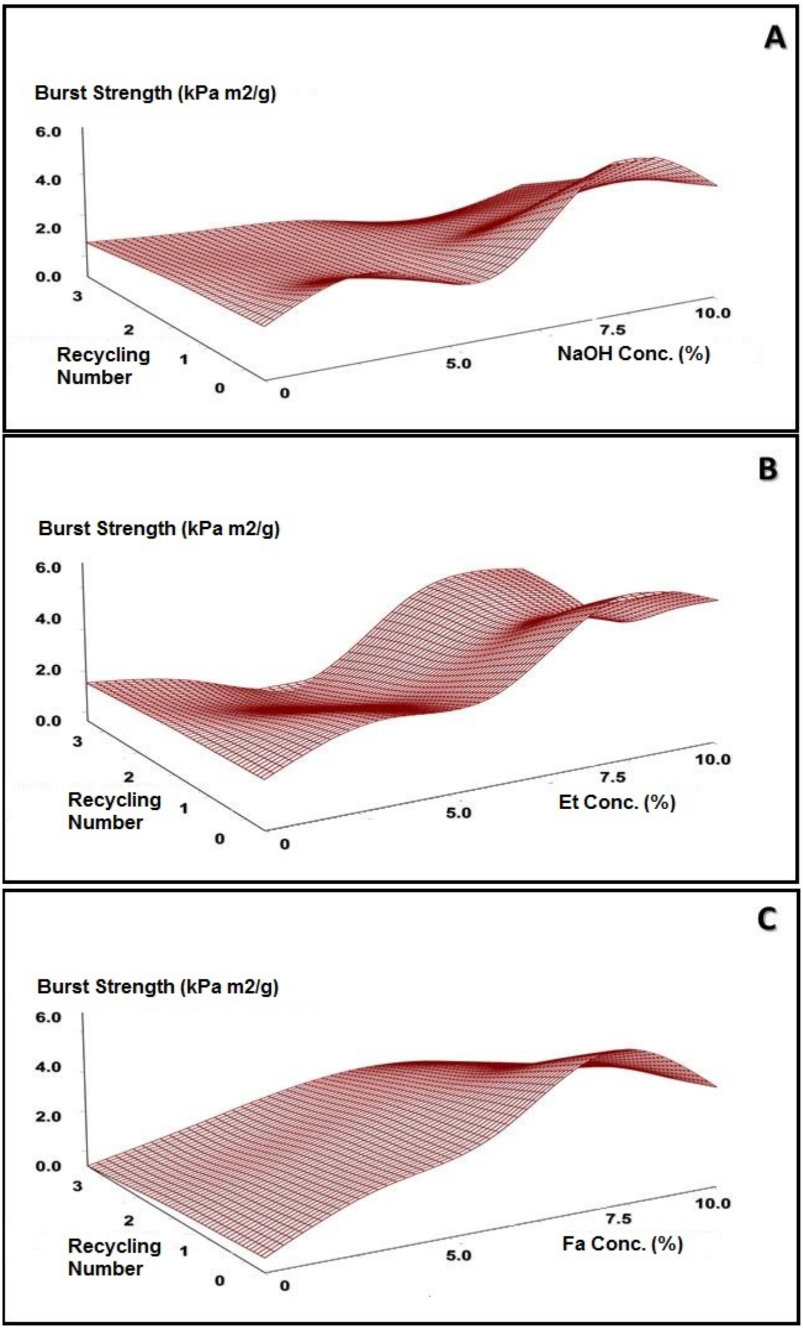

Fig. 2. Burst strength of recycled papers

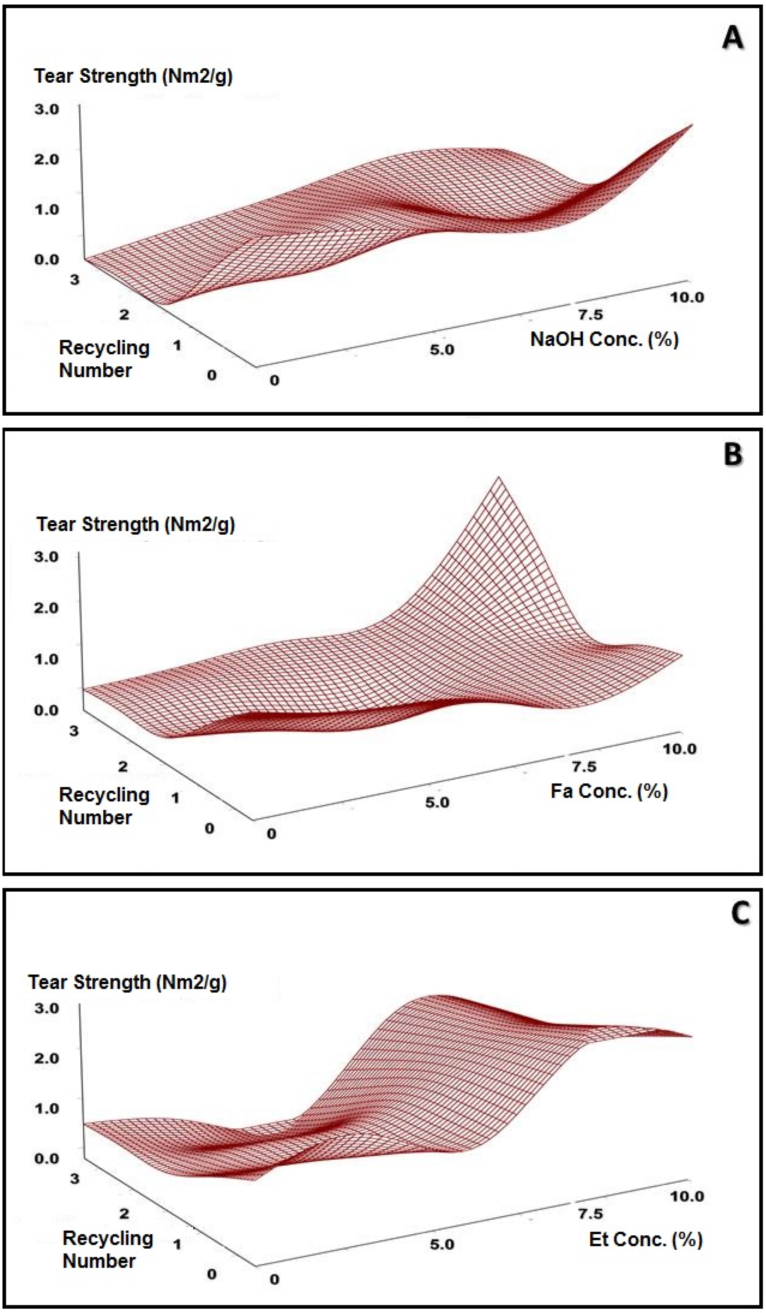

Fig. 3. Tear strength of recycled papers

In figure 2, similar trends were observed for the burst strengths of papers. Similarly, up to a 7.5% chemical charge, there is a level of improvement; beyond this level (10%), a decreasing tendency was observed for all three chemical treatments of recycled fibres.

In figure 3, considerably different results were observed for tear strengths of paper compared with those in figures 1 and 2. It can be realised that a sodium hydroxide concentration primarily has positive effects on improving tear strengths of paper (fig. 3A). However, both recycling number and formamide concentration are positively correlated with the tear strength of paper (fig. 3B). Moreover, ethyl acetate treatments (fig. 3C) show a similar trend in tensile and burst strength graphs (fig. 1 and 2). Hence, for up to a 7.5% ethyl acetate charge, there is a level of improvement; beyond this level (10%), some decreasing tendency is observed.

In contrast with the tensile and burst strengths, a number of studies have shown that chemical fibre recycling causes a major reduction in tensile and burst strength, with a lesser reduction in density and stretch [Howard and Bichard 1992; Biermann 1993; Minor 1994; Bajpai 2014]. Increases in tear strength, opacity, and air permeability are usually reported. These changes have been largely ascribed to decreased swelling capacity and flexibility of the fibres. However, tear strength is a complicated effect in terms of fibre properties [Fernandez and Young 1996]. However, the reduction in tensile or burst strength and the increase in tear strength were not merely caused by the bonding potential of recycled fibres. Curl formation is also considered to be an important factor affecting the strength of recycled pulp.

Conclusions

It is well established that recycling brings about irreversible changes in cellulosic bonding potential. Therefore, there is a need for increased understanding with regards to the changes that take place in the structure of recycled cellulosic fibres. Chemical treatment of pulp is a means to increase and regain the bonding potential of pulp. Understanding the fundamental change and bonding potential of recycled cellulosic fibres may open the possibility to increase recycling of waste paper.

It has been realised that ethyl acetate and formamide are useful organics for the chemical treatment of recycled fibres to improve swelling and bonding (strength) of cellulose fibres. This may have some attractive economic advantages.

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List of standards

ASTM E313 Standard practice for calculating yellowness and whiteness indices from instrumentally measured color coordinates

ISO 2469:2014 Paper, board and pulps – Measurement of diffuse reflectance factor
TAPPI T205 om-88 Forming hand sheets for physical tests of pulp
TAPPI T220 sp-96 Physical testing of pulp hand sheets
TAPPI T403 Bursting strength of paper
TAPPI T414 Internal tearing resistance of paper (Elmendorf-type method)
TAPPI T425 om-96 Opacity of paper (15/d geometry, illuminant A/2, 89% reflectance backing and paper backing)
TAPPI T460 om-02 Air resistance of paper (Gurley method)
TAPPI T494 om-96 Tensile properties of paper and paperboard (using constant rate of elongation apparatus)

Acknowledgements

The authors wish to thank the financial support received for this research from the Scientific and Technical Research Council of Turkey (TÜBITAK), Project number: 110O555.

Submission date: 31.03.2017

Online publication date: 22.11.2017