Physical and optical properties of steam-exploded laser-printed paper

ARVIND K. SHARMA, WILLIAM K. FORESTER, AND ELLSWORTH H. SHRIVER

ABSTRACT

Laser-printed paper was pulped by the steam-explosion process. A full-factorial experimental design was applied to determine the effects of key operating variables on the properties of steam-exploded pulp. The variables were addition level for pulping chemicals (NaOH and/or Na_2SO_3), digester pressure, digester residence time, and addition level for dispersant. Steam explosion removed laser toners from the fibers and dispersed the particles, as evidenced by the higher sheet brightness and opacity of exploded pulp compared with an unexploded control pulp. However, the fiber-bonding ability of exploded pulp was lower than that for unexploded pulp, as evidenced by lower tensile index and relative bonded area. Zero-span breaking length of exploded pulp also was lower, indicating that explosive discharge damaged the fibers.

THE RAPID EXPANSION IN COLLECtion of recycled paper is stimulating research into methods of upgrading secondary fibers for use in increasingly demanding grades of paper and paperboard. Efforts have been directed mainly toward development of equipment and processes capable of producing cleaner fibers.

There are several processes for recycling paper, depending on the quality of the raw material and the desired quality of the end product. Chesapeake Corp. (Richmond, VA) and Stake Technology (Toronto, ON), a developer of a steam-explosion digester, introduced a steam-explosion process to pulp post-consumer papers (e.g., newsprint, corrugating paperboard, and sorted office waste) in a single-feed stream for recycling. Capital and operating costs for the equipment are reported to be two-thirds of the amount required for conventional paper-recycling plants *(1)*. The system also has a low impact on the environment, since it uses no chemicals, except in a few of the most difficult cases, and produces no hazardous by-products *(2)*.

Steam-explosion pulping (SEP) has been proposed as an alternative to the conventional chemimechanical pulping (CMP) and chemithermomechanical pulping (CTMP) processes *(3)*. The distinctive features of the SEP process include a short cooking time at high temperature and pressure in saturated steam. The cook is followed by explosive discharge of pulp when the pressure in the digester is instantaneously released. The exploded pulp is then beaten in an atmospheric refiner and, depending on the end use, bleached.

Steam-exploded pulps are reported to have strength properties similar to those of conventional ultra-high-yield CMP or CTMP pulps in the case of spruce, with strengths up to 50% higher in the case of aspen, birch, larch, or jack pine *(4)*. Explosion pulps are also reported to require much lower specific refining energy than CMP and CTMP *(5)*. One pilot-scale study showed that chemical impregnation of spruce chips with sodium sulfite followed by steam explosion produced a pulp with properties superior to CTMP and energy savings of 25% *(6)*. In another pilot-scale study, coated paper and groundwood paper were deinked using steam-explosion and conventional processes *(7)*. Pulp from both systems had comparable strength properties. Image analysis of pulps produced from mixed office waste showed that the steam-exploded pulp contained fewer and smaller particles than the pulp produced using the conventional method.

Despite these reported successes for steam-explosion pulping, there is little information explaining how or why this process provides such exceptional results. In a study of exploded and unexploded black spruce chips, Law and Bi *(8)* found that the sudden decompression of steamed chips did not improve pulp properties or reduce refining energy. In fact, the force of the explosive discharge and the resultant impact of the steamed chips against the walls of a blow vessel may damage the fibers and reduce the mechanical properties of the pulp. Law and Valade *(9)* also demonstrated that explosive discharge following high-yield explosion pulping does not liberate fibers from steamed chips.

Given the available deinking technologies and the projected supplies of recycled paper, steam explosion shows promise as a recycling process. Beyond the lower capital and operating costs, the steam-explosion method reportedly can recycle furnishes not normally recyclable *(10)*. The process also does not require surfactant/dispersant or pulping chemicals. A feeder, digester, and discharge mechanism (Stake Technology) use process steam to explode recovered paper, old newspapers (ONP), old corrugated containers (OCC), and mixed office waste (MOW). High temperature and

pressure are reported to break down ink particles so that they can be washed away without flotation *(11)*. Contaminants are removed by screening.

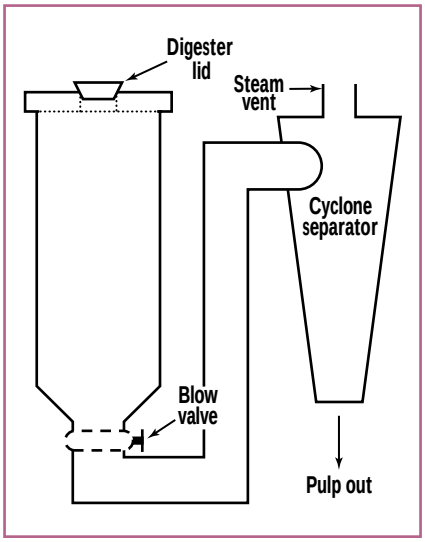
The present study examines the use of steam explosion to pulp laser-printed paper. Laser-printed inks contain thermoplastic resins, which are difficult to detach from the fibers and do not break up during pulping. The current approach is to deink such furnishes using expensive equipment to mechanically detach, disperse, and finally remove the ink particles. In the steam-explosion process, the combination of heat and pressure is proposed as a means of dislodging the ink particles and then breaking them down so that they can simply be rinsed away.

The study was carried out by investigating the effects of key independent pulping variables—addition of pulping chemicals (NaOH and/or Na_2SO_3), digester pressure, digester retention time, and addition of dispersant. The research goal was to determine the effects of these factors on the optical properties, bonding ability, and the strength of recycled fibers. The optical and physical properties of an unexploded pulp served as a control.

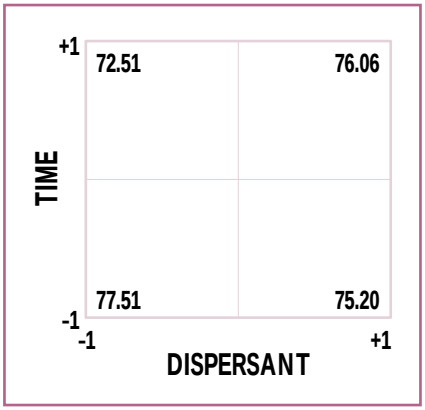
Variable	Low conditions	High conditions
Pulping chemical, %[a]		
NaOH	0	2
Na_2SO_3	0	2
Pulping pressure, psig[b]	200	400
Pulping time, min	2	4
Dispersant, %[a]	0	0.25

[a] Based on dry weight of paper
[b] Blow pressure = 500 psig

1. Independent variables for steam-explosion experiments



1. Digester used in steam-explosion trials



3. Plot of dispersant–time interaction for pulp brightness

EXPERIMENTAL

Design

Four factors were evaluated at two levels: addition of pulping chemicals (NaOH and/or Na_2SO_3), pulping pressure, pulping time, and dispersant addition. Table I shows the low and high conditions for each of the steam-explosion variables. The setup for the experimental design is listed in Table II. A full-factorial design (32 runs) was used to develop and verify the model relating the independent variables (pulping chemicals, pressure, residence time, dispersant) to the dependent optical properties (brightness, opacity, light-scattering coefficient, and light-absorption coefficient).

Normal probability plots and analysis of variance (ANOVA) were used to compare the important effects and interactions involved in the experiments *(12)*. It was assumed that four-way and five-way interactions of the variables were not significant, so only two- or three-way interactions were considered.

The bonding ability of recycled fibers was evaluated by calculating tensile index and relative bonded area (RBA). Fiber damage was evaluated by measuring the zero-span breaking length of steam-exploded pulp made without pulping chemicals. The physical and optical properties of steam-exploded pulp were compared with results obtained for an unexploded pulp prepared without the use of chemicals.

Materials

The laser-printed paper was first shredded or chipped into pieces measuring roughly 1–2-in.^{2}. Shredding was done using a hammer mill. Dispersant [alkyl methyl pyrrolidone (BRD 288, Buckman Laboratories)] was added at a rate of 0.25% based on dry paper weight. When used in conjunction with laser-printed office waste, the dispersant works rapidly to disperse the toner and improve deinking efficiency *(13)*.

PULPING VARIABLES

Run No.	Chemical addition NaOH	Chemical addition Na_2SO_3	Dispersant	Pressure	Time
No chemical					
1	–	–	–	+	–
2	–	–	–	+	+
3	**–**	**–**	**–**	**–**	**–**
4	–	–	–	–	+
5	–	–	+	+	–
6	**–**	**–**	**+**	**+**	**+**
7	–	–	+	–	–
8	–	–	+	–	+
NaOH					
9	+	–	+	+	–
10	**+**	**–**	**+**	**+**	**+**
11	+	–	+	–	–
12	+	–	+	–	+
13	+	–	–	+	–
14	+	–	–	+	+
15	**+**	**–**	**–**	**–**	**–**
16	+	–	–	–	+
Na_2SO_3					
17	–	+	–	+	–
18	–	+	–	+	+
19	**–**	**+**	**–**	**–**	**–**
20	–	+	–	–	+
21	–	+	+	+	–
22	**–**	**+**	**+**	**+**	**+**
23	–	+	+	–	–
24	–	+	+	–	+
NaOH + Na_2SO_3					
25	+	+	+	+	–
26	**+**	**+**	**+**	**+**	**+**
27	+	+	+	–	–
28	+	+	+	–	+
29	+	+	–	+	–
30	+	+	–	+	+
31	**+**	**+**	**–**	**–**	**–**
32	+	+	–	–	+

* Plus signs (+) denote high conditions; minus signs (–) denote low conditions. The eight runs in bold type (Runs 3, 6, 10, 15, 19, 22, 26, 31) represent operation at low and high conditions for all four permutations of chemical addition. Values for high and low conditions are listed in Table I.

II. Experimental design *

Run No.	Pulping condition
No pulping chemicals	
Run 3	Low [a]
Run 6	High [b]
NaOH [c]	
Run 10	High [b]
Run 15	Low [a]
Na_2SO_3 [c]	
Run 19	Low [a]
Run 22	High [b]
NaOH + Na_2SO_3 [d]	
Run 26	High [b]
Run 31	Low [a]

[a] 200-psig digester pressure, 2-min retention time, no dispersant
[b] 400-psig digester pressure, 4-min retention time, 0.25% dispersant
[c] 2% based on dry weight of paper
[d] 2% NaOH and 2% Na_2SO_3 based on dry weight of paper

III. Pulping conditions for key runs during steam-explosion experiments

Pulp preparation

Four pounds of shredded paper was soaked for 5 min for each trial. For trials involving the use of pulping chemicals and/or dispersant, these materials were added during the presoak. The sodium hydroxide (NaOH) and sodium sulfite (Na_2SO_3) were added at a rate of 2.0% based on dry paper weight. After the presoak, the paper was drained for 5 min to yield a final consistency of 27%. The paper was then packed into the digester and the lid was sealed.

Digester pressure was raised to 100 psig within about 10 s. Timing began at this point, with the pressure increased to the specified target (200 psig or 400 psig) within 5 s and maintained at that pressure until 15 s before the blow. The pressure was then increased to the blow pressure of 500 psig over a span of 15 s. Pulp was discharged immediately at 500 psig. Digester retention from the start of timing (at 100 psig) to blow was 2 min and 4 min at each of the target pressures (200 psig and 400 psig).

The explosion removed the paper from the digester and conveyed it to a cyclone separator, where the pulp was collected and the steam vented off. Figure 1 shows the design of the digester (steam gun) used for the steam-explosion trials.

Unexploded pulp was prepared in a Morden slush maker to simulate conventional fiber dispersion in a Hydrapulper. Water was first added and heated by steam to 115°F. The steam was then shut off, and the shredded paper was added to achieve 6% consistency during pulping, which was carried out without

the aid of pulping chemicals or dispersant. The slush maker was run for 10 min and the pulp was removed. This unexploded pulp served as an untreated control for comparison with steam-exploded pulps produced without pulping chemicals or dispersant.

Refining, sheet forming, and testing

Tensile index and relative bonded area were determined for pulps produced during steam-explosion Runs 3, 6, 10, 15, 19, 22, 26, and 31, which correspond to the high and low conditions of treatment at the four possible permutations of chemical addition. The pulping conditions for these runs are defined in Table III. Pulps from each run were refined in a PFI mill at 10% consistency in 30-g batches for 12,000 revolutions. The refined pulp was further disintegrated in the British disintegrator at 1.25% consistency and then diluted to 0.3% consistency for freeness measurement and formation of handsheets. Unexploded pulp was similarly refined in the PFI mill and prepared for handsheet making. The choice of keeping the refining level at 12,000 revolutions was based on several refining trials carried out to achieve optimum tensile strength.

Optical and physical properties of the steam-exploded pulp and unexploded pulp were measured using handsheets made on a British sheet former. The handsheets were formed to give a sheet weight of 1.14–1.26 oven-dry g (basis weight of 60 g/m^2). All handsheets were kept in a preconditioning room held at 35% RH (relative humidity) and 72°F for 24 h and then for 2 h in the conditioning room held at 50% RH and 72°F. Single replicates were made from all runs.

Handsheets were tested for optical and physical properties using standard instruments according to TAPPI test methods. Properties

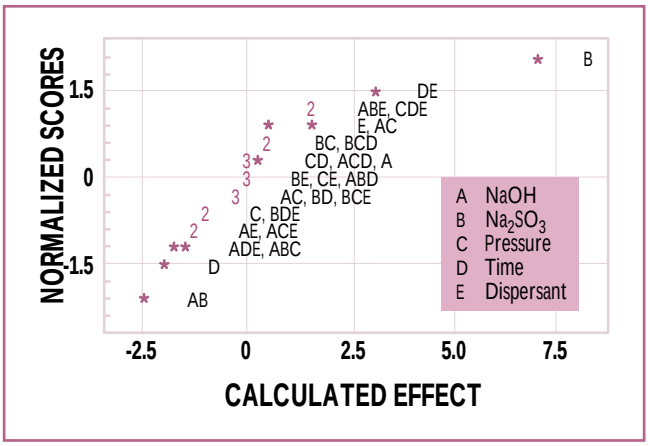
Run No.	Brightness, %	Opacity, %	Light-scattering coefficient, m^2/kg	Light-absorption coefficient, m^2/kg
No chemical				
1	74.7	83.3	39.9	1.32
2	58.0	82.7	35.6	2.58
3	73.6	85.8	40.5	1.36
4	69.0	84.0	41.3	1.95
5	67.1	85.2	39.6	2.14
6	76.6	83.5	40.0	1.49
7	73.2	84.4	41.4	1.35
8	71.8	85.2	42.6	1.77
NaOH				
9	70.8	83.5	40.9	1.55
10	71.3	82.2	38.6	1.57
11	73.0	82.1	37.1	1.29
12	73.2	82.2	38.4	1.35
13	76.1	82.3	38.6	1.09
14	74.0	82.8	39.2	1.09
15	73.1	82.5	41.2	1.40
16	74.0	82.9	41.1	1.29
Na_2SO_3				
17	82.6	82.2	39.4	0.90
18	77.5	82.1	39.8	1.34
19	82.7	82.0	40.5	0.88
20	75.9	84.0	42.4	1.29
21	81.6	82.7	41.7	1.00
22	79.7	84.0	42.3	1.06
23	80.1	81.1	39.4	0.93
24	78.6	82.7	41.9	1.02
NaOH + Na_2SO_3				
25	75.9	83.6	42.4	1.24
26	77.7	81.8	41.4	1.07
27	79.9	84.5	39.9	1.01
28	79.6	81.3	39.6	1.05
29	77.2	80.1	37.7	1.04
30	75.6	79.7	36.6	0.99
31	80.1	82.7	39.6	1.35
32	76.1	83.0	41.2	1.32

IV. Optical properties of steam-exploded pulps

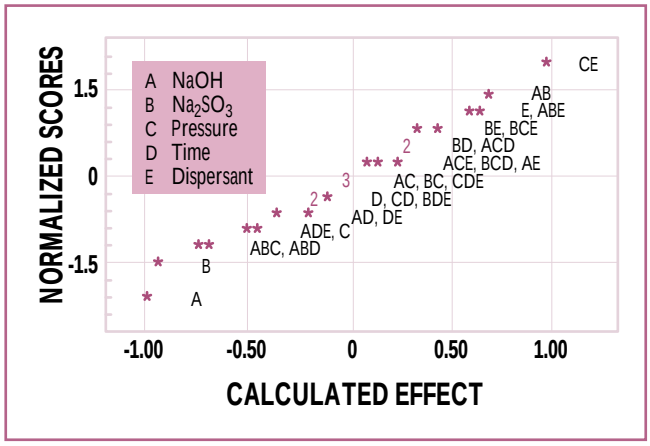
Term	Effect	Coeff.	Std. Coeff.	*t*-value	*p*-value
Constant	...	75.322	0.5578	135.03	0.000 *
Na_2SO_3	6.956	3.478	0.5578	6.24	0.000 *
Dispersant	0.619	0.309	0.5578	0.55	0.584
Time	–2.069	1.034	0.5578	–1.85	0.075
Dispersant x time	2.931	1.466	0.5578	2.63	0.014 *

* Significant at 5% level

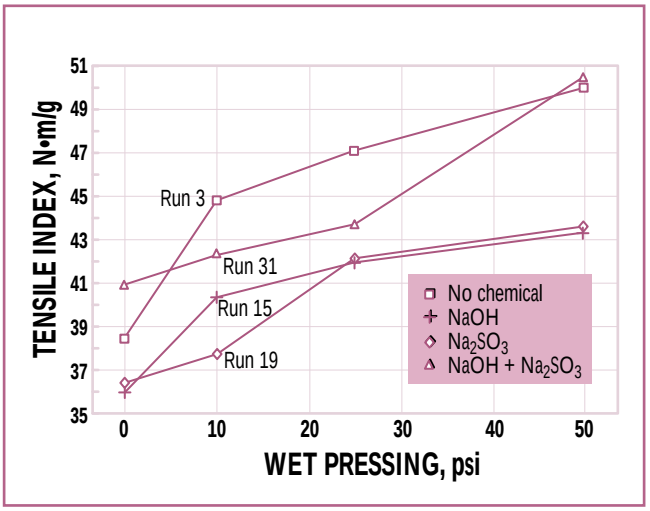
V. Estimated effects and coefficients for brightness of steam-exploded pulps



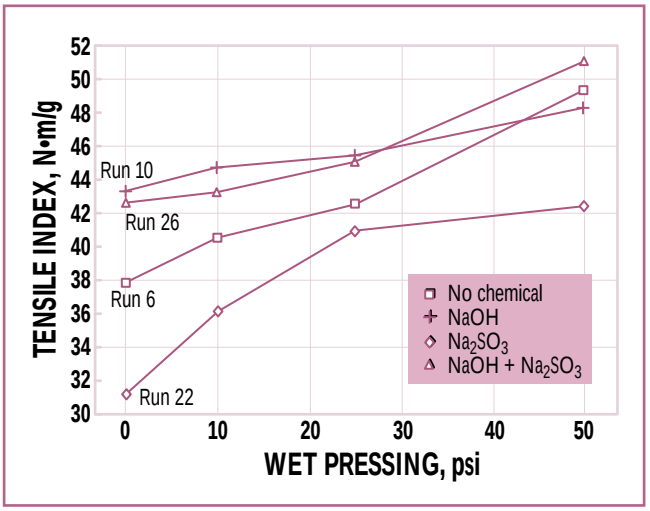
2. Normal probability plot of factor effects for pulp brightness (The numerals depict the position and number of overlapping data points.)



4. Normal probability plot of factor effects for pulp opacity (The numerals depict the position and number of overlapping data points.)



5. Tensile index as a function of wet pressing for runs at low pulping conditions



6. Tensile index as a function of wet pressing for runs at high pulping conditions

obtained from both the steam-exploded pulp and unexploded pulp were compared.

RESULTS AND DISCUSSION

Optical properties of steam-exploded pulps

Brightness. Brightness data for the 32 steam-explosion runs are given in Table IV. The runs made with no chemical addition showed brightness in the range 58.0–76.6%. The runs made with 2% sodium hydroxide showed brightness in the range 70.8–76.1%. The runs with 2% sodium sulfite had brightness in the range 75.9–82.7%. When sodium hydroxide and sodium sulfite were used together at 2% each, brightness was in the range 75.6–80.1%.

A normal probability plot of factor effects was developed to determine the significant factors and interacting factors (two way or three way) affecting brightness. The plot is shown in Fig. 2. In a normal probability plot, the effects falling along a straight line are assumed to be negligible. Any point that deviates considerably from the straight line represents a potentially significant effect. As seen in Fig. 2, the factor effects B (sodium sulfite) and DE (interaction effect of time and dispersant) deviate considerably from the straight line. Consequently, these are considered to be the significant effects on pulp brightness.

The estimated effects and coefficients for brightness are given in Table V. The table indicates that the factor effect of sodium sulfite is

Source	Degrees of freedom	Seq. sum of squares	Adjusted sum of squares	Adjusted mean squares	*F*-value	*p*-value
Main effects	3	424.416	424.416	141.472	14.21	0.000 *
2-way interactions	1	68.738	68.738	68.738	6.90	0.014 *
Residual error	27	268.841	268.841	9.957	...	...
Lack of fit	3	8.743	8.743	2.914	0.27	0.847
Pure error	24	260.097	260.097	10.837	...	...
Total	31	761.955	...	...	...	...

* Significant at 5% level

VI. Analysis of variance table for brightness of steam-exploded pulps

6.956, and the interaction effect of dispersant and time is 2.931. The ANOVA table for brightness is shown in Table VI. The *p*-value of the main effects (sodium sulfite, dispersant, and time) is 0.00, and the *p*-value for the dispersant–time interaction is 0.014. Both values are less than 0.05, which means that we can state—with 95% confidence—that both effects are statistically significant.

The interaction effect of dispersant and time is explained in Fig. 3, which shows that maximum brightness was obtained when dispersant and time were both at the low level. Possibly, less dispersion of the ink caused more specks but less loss in brightness. When time was kept at a low level, and dispersant at a high level, brightness was reduced by 2.31 units. This probably occurred when ink was well dispersed but not washed out. Under the conditions maintained in this experiment, the best brightness was achieved for the treatment with sodium sulfite at the lowest values for digester residence time (2 min) and dispersant (none).

Opacity. Opacity data for the 32 steam-explosion runs are given in Table IV. Pulp from the runs made without pulping chemical had opacities of 82.7–85.8%. The runs with sodium hydroxide had opacities of 82.1–83.5%, while the runs with sodium sulfite had opacities of 81.1–84.0%. When both sodium hydroxide and sodium sulfite were used together, opacities were 79.7–84.5%. The highest opacity achieved was 85.8%, when both pulping chemicals were absent. Thus, the use of pulping chemicals reduced opacity, in agreement with the expectation that higher fiber bonding will reduce opacity.

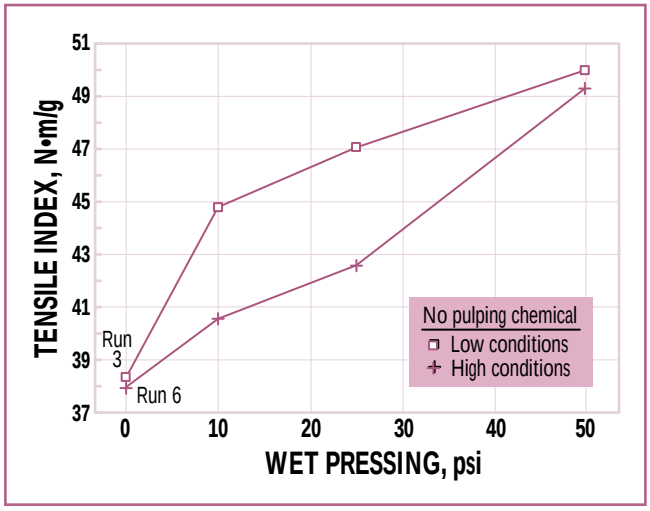
The normal probability plot of factor effects for opacity is shown in Fig. 4. The plot shows no statistically significant effects.

Pulp type	Wet pressing, psi	Tensile index, Nm/g	RBA, %
Run 3 (no pulping chemical)	0	38.4	28.2
	10	44.8	32.1
	25	47.1	32.5
	50	50.0	37.4
Run 15 (NaOH)	0	35.9	40.1
	10	40.3	45.2
	25	41.9	46.8
	50	43.3	48.4
Run 19 (Na_2SO_3)	0	36.4	32.8
	10	37.7	36.4
	25	42.1	38.8
	50	43.6	40.6
Run 31 (NaOH + Na_2SO_3)	0	40.9	29.5
	10	42.3	33.2
	25	43.7	34.2
	50	50.5	37.9

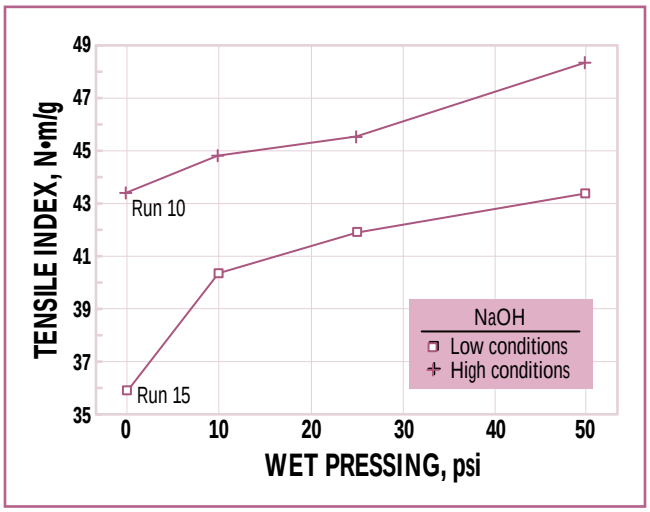
* 200-psig digester pressure, 2-min retention time, no dispersant

VII. Tensile index and RBA at four levels of wet pressing for exploded pulps produced at low conditions of treatment *

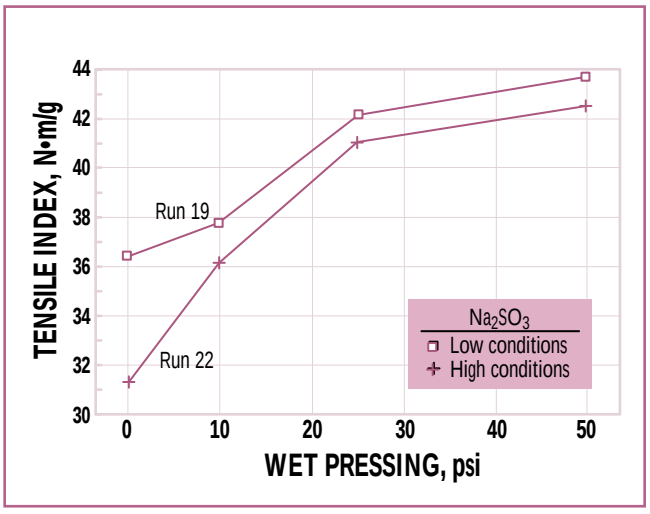
Light-scattering coefficient. Data for the light-scattering coefficients obtained during the 32 steam-explosion runs are given in Table IV. The scattering coefficients of the runs made without pulping chemical were in the range 35.6–42.6 m^2/kg. The runs with sodium hydroxide had scattering coefficients of 37.1–41.2 m^2/kg, while the runs with sodium sulfite had scattering coefficients of 39.4–42.4 m^2/kg. When both pulping chemicals were used together, the scattering coefficients were 36.6–



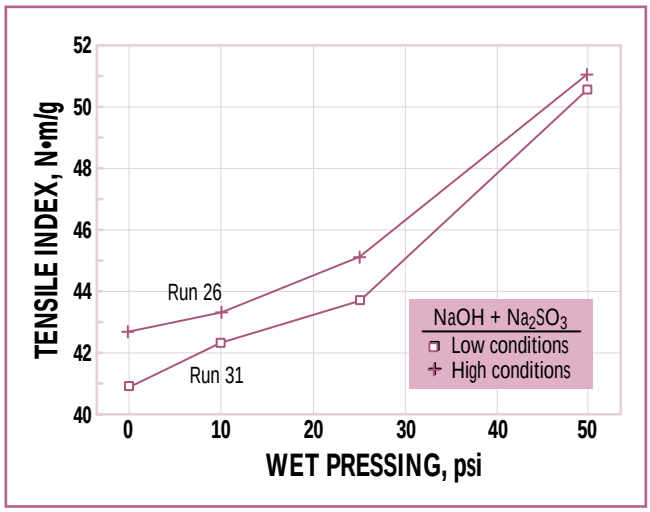
7. Tensile index as a function of wet pressing for chemical-free runs at low and high pulping conditions



8. Tensile index as a function of wet pressing for NaOH runs at low and high pulping conditions



9. Tensile index as a function of wet pressing for Na_2SO_3 runs at low and high pulping conditions



10. Tensile index as a function of wet pressing for NaOH + Na_2SO_3 runs at low and high pulping conditions

42.4 m²/kg. These data show that addition of pulping chemical—either sodium hydroxide or sodium sulfite or both in conjunction—did not affect the scattering coefficient. This finding was unexpected, since addition of pulping chemicals increases fiber bonding and thus should reduce the scattering coefficient.

A normal probability plot of factor effects for scattering coefficient confirmed this finding. The only effect that appeared marginally significant was the interaction of pressure and dispersant.

Light-absorption coefficient. Data for the light-absorption coefficients obtained during the 32 steam-explosion runs are given in Table IV. The absorption coefficients of the pulps made without chemical addition were in the range 1.32–2.58 m²/kg. The runs made with 2% sodium hydroxide had absorption coefficients of 1.09–1.57 m²/kg. The pulps prepared with 2% sodium sulfite had absorption coefficients of 0.88–1.34 m²/kg. When both pulping chemicals were used together at 2% each, the absorption coefficients were 0.99–1.35 m²/kg. These data show that the runs made without pulping chemicals had the highest range of absorption coefficient.

A normal probability plot of factor effects for absorption coefficient showed that all effects lie reasonably close to a straight line, with the exception of sodium sulfite, indicating that sodium sulfite had a significant effect. The use of sodium sulfite

alone reduced the absorption coefficient, as expected from bleaching theory. When sodium sulfite was used in conjunction with sodium hydroxide, the value of the absorption coefficient did not increase because of a canceling effect.

Bonding ability of steam-exploded recycled fibers

The bonding ability of steam-exploded recycled fibers was determined by calculating tensile index and relative bonded area. Eight runs (the four permutations of chemical addition at low and high pulping conditions) were evaluated at four levels of wet pressing. The layout of the runs and resultant data for strength properties are listed in Tables VII and VIII. Table VII shows the data for low conditions of treatment, i.e., 200-psi pressure, 2-min residence time, no dispersant. Table VIII shows the data for high conditions of treatment, i.e., 400-psi pressure, 4-min residence time, 0.25% dispersant.

Figure 5 shows tensile index achieved for the low conditions of treatment at the four levels of wet pressing. The values of tensile index for the run with no pulping chemical (Run 3) are higher than for the run with 2% sodium hydroxide (Run 15). This was surprising, since sodium hydroxide was expected to give higher tensile strength because of its ability to swell the fibers and subsequently increase bonding. However, no consistent differences were observed with the addition of sodium hydroxide at low conditions. Similar results were obtained for the run with 2% sodium sulfite (Run 19), with chemical-free pulping showing higher tensile index at all four levels of wet pressing. When sodium hydroxide and sodium sulfite were used together at 2% each (Run 31), the tensile-strength data were similar to that of the run with no chemical addition. Run 31 showed better tensile strength development compared with the runs made of 2% sodium hydroxide or 2% sodium sulfite alone.

Pulp type	Wet pressing, psi	Tensile index, Nm/g	RBA, %
Run 6 (no pulping chemical)	0	38.0	30.8
	10	40.6	35.0
	25	42.6	37.2
	50	49.3	40.9
Run 10 (NaOH)	0	43.4	53.8
	10	44.8	59.3
	25	45.5	59.7
	50	48.3	61.1
Run 22 (Na_2SO_3)	0	31.3	26.9
	10	36.2	33.9
	25	41.0	35.9
	50	42.4	37.4
Run 26 (NaOH + Na_2SO_3)	0	42.7	34.3
	10	43.3	37.6
	25	45.1	41.3
	50	51.0	44.6

* 400-psig digester pressure, 4-min retention time, 0.25% dispersant

VIII. Tensile index and RBA at four levels of wet pressing for exploded pulps produced at high conditions of treatment *

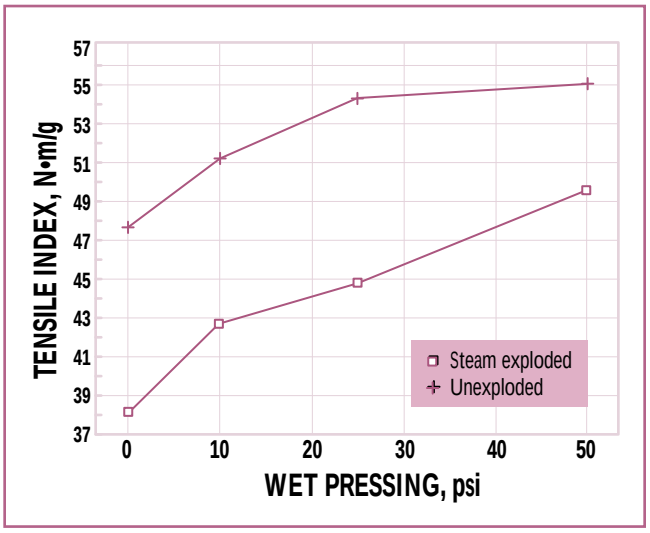
The RBA data for the runs at low conditions (Table VII) show a different trend than tensile index. For example, Runs 15 and 19 had lower tensile index than Runs 3 and 31, but their RBA was higher. The biggest difficulty in determining RBA is obtaining the value for the light-scattering coefficient of the unbonded sheet. This value is determined by extrapolating a plot of the scattering coefficient against tensile strength for a series of sheets with different degrees of either beating or wet pressing. This extrapolation is often doubtful because of the variation of not only the bonded area but also the total surface area *(14)*.

Table VIII shows tensile index and RBA under high conditions of treatment. Figure 6 graphs the trends for tensile index. Under high conditions, sodium hydroxide swelled the fibers better and improved the fiber bonding, resulting in higher strength properties (Run 10). The strength was considerably lower when sodium sulfite was used alone at 2% (Run 22). When both pulping chemicals were used together at 2% each (Run 26), the tensile index was 2–3% lower than with sodium hydroxide alone and 3–4% higher compared with the runs with no pulping chemical (Run 6). The RBA data in Table VIII indicate the same pattern as tensile strength.

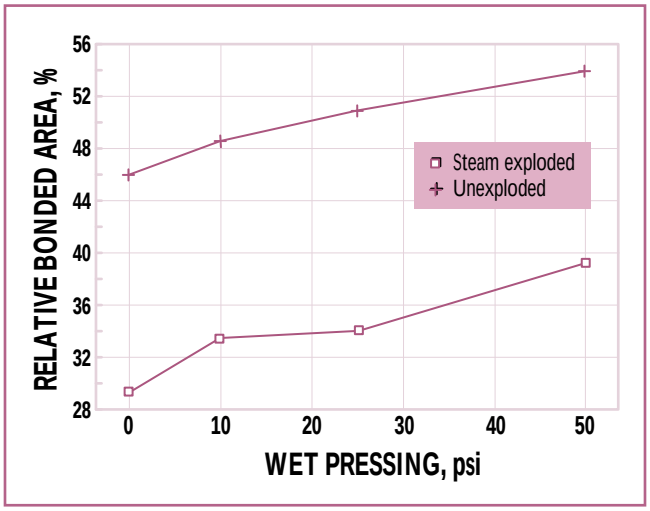
Pulp type	Zero-span breaking length, km
Exploded pulps	
Run 3 (low conditions)	0.72
Run 6 (high conditions)	0.86
Average	0.79
Unexploded pulp	2.70

IX. Fiber strength of unrefined pulps produced without pulping chemicals or dispersants

Figures 7–10 show the tensile index of the pulps at low and high



11. Tensile index as a function of wet pressing for chemical-free steam-exploded pulps (average of high and low pulping conditions) and unexploded pulp



12. RBA as a function of wet pressing for chemical-free steam-exploded pulps (average of high and low pulping conditions) and unexploded pulp

ZERO-SPAN BREAKING LENGTH, km

Pulp type	No wet pressing	10-psi wet pressing	25-psi wet pressing	50-psi wet pressing
Exploded pulps				
Run 3 (low conditions)	1.20	1.12	1.08	1.06
Run 6 (high conditions)	1.70	1.63	1.31	1.23
Average	1.45	1.38	1.20	1.15
Unexploded pulp	1.94	1.87	1.80	1.53

X. Fiber strength of refined pulps produced without pulping chemicals or dispersants at four levels of wet pressing

conditions of treatment for the four levels of pulping chemical (no chemical, 2% sodium hydroxide, 2% sodium sulfite, 2% sodium hydroxide + 2% sodium sulfite, respectively). Figure 7 indicates that steam-exploded pulp produced without pulping chemicals had higher tensile strength at low conditions than at high conditions. In two cases, the strength was 2–3% higher, while the strength was 8–9% higher in the other two cases. The pulp produced with sodium hydroxide had 10–15% higher tensile strength at high conditions than at low conditions, as seen in Fig. 8. Sodium sulfite addition resulted in 2–3% higher tensile strength at the low conditions as compared with the high conditions, as seen in Fig. 9. The combination of both pulping chemicals produced an average 2–3% increase at the high conditions compared with the low, as seen in Fig. 10. The RBA data differed considerably between low and high conditions, as seen in Tables VII and VIII, respectively.

Comparison of steam-exploded pulps with unexploded pulp

Fiber strength. Fiber strength was studied in an effort to determine whether fibers suffered damage during steam explosion. The zero-span breaking length of steam-exploded pulps was measured and compared with the unexploded control pulp, which was prepared without the use of pulping chemicals. Steam-explosion Runs 3 and 6 were selected, since these represented the low and high conditions in the absence of pulping chemicals. The average zero-span breaking length of these runs was determined before refining and after refining and compared with the unexploded pulp (no pulping chemical). Tables IX and X show the data for zero-span breaking length for unrefined and refined pulps, respectively. As seen in Table X, the refined unexploded pulp had about 35–40% higher zero-span breaking length than refined steam-exploded pulps from Runs 3 and 6 at the four different levels of sheet pressing. This shows that the steam-explosion process severely damaged the fibers.

Optical and strength properties. The optical and strength properties of the unexploded pulp (no chemicals) were compared with those obtained for steam-explosion Runs 3 and 6, the two runs that represented the low and high conditions of treatment without a pulping chemical.

KEYWORDS
Bonded area, chemicals, dispersants, experimental design, exploded pulps, lasers, optical properties, physical properties, pressure, prints, pulping, pulps, reclaimed fibers, recycling, steaming, tensile strength, time, waste papers.

Pulp type	Brightness, %	Opacity, %	Light-scattering coefficient, m^2/kg	Light-absorption coefficient, m^2/kg
Exploded pulps				
Run 3 (low conditions)	73.6	85.8	40.5	1.36
Run 6 (high conditions)	76.6	83.5	40.0	1.49
Average	75.1	84.7	40.3	1.43
Unexploded pulp	67.8	83.6	37.4	1.91

XI. Optical properties of pulps produced without pulping chemicals or dispersants

We originally considered averaging the optical and strength properties for all eight of the runs with no pulping chemical. However, some of these runs showed unusual optical properties, so the average results for the eight runs are not presented.

Table XI shows the comparison of optical properties. The steam-exploded pulp had a higher brightness compared with unexploded pulp because of its lower absorption and higher scattering coefficients. From this, it can be inferred that steam explosion removed the toner from the cellulose fibers and dispersed the particles in the pulp suspension, which permitted the particles to be washed out of the fibers during sheet formation. The opacity of exploded pulp also was higher than that of unexploded pulp.

Figure 11 shows that the tensile index of unexploded pulp was about 18–20% higher than the average tensile index of Runs 3 and 6. This difference was more pronounced for the RBA, as seen in Fig. 12. The unexploded pulp had 40–45% higher RBA compared with the steam-exploded pulp at all four sheet-pressing levels.

CONCLUSIONS

Steam-explosion pulping of laser-printed papers was studied using a full-factorial experimental design. The independent variables were level and type of pulping chemical, digester pressure, digester retention time, and level of dispersant. Pulp quality was evaluated by measuring optical and strength properties. The results were as follows:

- Sodium sulfite was the most significant factor in increasing the brightness. The best results for brightness were achieved with a short residence time in the digester (2 min) and no dispersant addition during pulping.
- The highest opacity was achieved when no pulping chemicals were added during pulping. Other factors such as pulping pressure, residence time, and dispersant did not affect opacity.
- Addition of pulping chemicals did not affect the light-scattering coefficient.
- Sodium sulfite reduced the absorption coefficient. When sodium sulfite was used in conjunction with sodium hydroxide, no reduction in absorption coefficient was observed. Other factors such as pulping pressure, residence time, and dispersant did not affect the absorption coefficient.
- Tensile strength with sodium hydroxide showed better results at high conditions of treatment. The combination of both pulping chemicals (NaOH and Na_2SO_3) had no significant effect on strength at low or high conditions of treatment.
- Data for relative bonded area (RBA) correlated with tensile strength at the high conditions but not at the low conditions. This was due to tensile strength being affected by fiber degradation.
- Comparison of exploded and unexploded pulps—both produced without pulping chemicals—showed that brightness was higher for the exploded pulp. The higher brightness indicates that explosion pulping dispersed the toner particles, which were then rinsed out during formation of handsheets.
- The tensile strength and RBA were higher for unexploded pulp than for steam-exploded pulp. Zero-span breaking length of steam-exploded pulp was much lower than the unexploded pulp. This shows that steam explosion caused some damage to the fibers. TJ

Sharma is a graduate student; Forester is director of the paper pilot plant; and Shriver is a research associate. All are affiliated with the Dept. of Paper Science and Engineering at Western Michigan University, Kalamazoo, MI 49008.

The authors thank Raymond L. Janes, professor of paper science, and John Crowell, associate professor of statistics, Western Michigan University, Kalamazoo, MI, for their invaluable suggestions and advice throughout this investigation.

Received for review May 26, 1995.
Accepted Sept. 2, 1995.

LITERATURE CITED

1. Stinson, S., *Chem. Eng. News* 69(1): 22(1991).
2. Bouchette, M., "Steam-explosion technology and fiber recycling," *1991 RPTA Production–Technical Seminar Proceedings*, RPTA, Elgin, IL, p.11.
3. Kokta, B. V., "Process for preparing pulp for papermaking," Canadian pat. 1,208,230 (Dec. 15, 1987).
4. Kokta, B.V. and Aziz, A., "Explosion pulping of aspen: Effect of operating conditions on resulting paper properties," *Proceedings of the 5th International Symposium on Wood and Pulping Chemistry*, TAPPI PRESS, Atlanta, 1989.
5. Tomasec M. and Kokta, B.V., *Tappi J.* 74(12): 119(1991).
6. Chaudhuri, P. B., *Tappi J.* 72(12): 196(1989).
7. Mentz, J. R., "Steam-explosion technology," *TAPPI 1991 Pulping Conference Proceedings*, TAPPI PRESS, Atlanta, pp. 83–4.
8. Law, K. N. and Bi, S. L., *Tappi J.* 72(1): 111(1989).
9. Law, K. N. and Valade, J. L., *J. Pulp Paper Sci.* 16(1): 41(1990).
10. Seifert, P., *Tappi J.* 77(2): 149(1994).
11. Schmidt, E., "Steam explosion as a pulping process," B.S. thesis, Western Michigan University, Kalamazoo, 1993.
12. Montgomery, D. C., *Design and Analysis of Experiments*, 3rd edn., John Wiley & Sons, New York, 1991, pp. 271–303.
13. BRD 288 information sheets, Buckman Laboratories, Memphis, TN.
14. Wigsten, A. and Baum, G. A., "Characterization of fiber networks," *1987 Paper Physics Fundamentals and Paper Making Practices Seminar Proceedings*, TAPPI PRESS, Atlanta, GA.