LABORATORY STUDY OF SHOE PRESSING FOR LOW BASIS WEIGHT PAPER APPLICATIONS

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ABSTRACT

Results of laboratory-simulated shoe pressing experiments on low basis weight handsheets are presented. Five different pressure pulse shapes, two dwell times (20 and 40ms), two average pressure levels (106 and 250 psi, simulating 4.7 inch and 2 inch shoes, respectively, at a press load of 500 pli)[1], and two basis weights (13.4 and 24.4 g/m^2) were investigated. In general, the expected water removal results were obtained, with the shoe press pulses better than the haversine control pulse, and high-pressure, short nip (narrow shoe) pulses better than low-pressure, long nip pulses. Short, high impulse shoes were significantly better than long, low impulse shoes for water removal. However, the high dewatering led to lower caliper (bulk) with higher tensile strength. For low basis weights, rewet is a major concern. This concern may be supported by the water removal data, which indicate that slight changes in the rate of depressurization (i.e., location of the peak pressure within the nip) appears to have a significant effect on outgoing solids. When the depressurization was steeper than average, higher solids were obtained than expected, and vice versa.

INTRODUCTION

The development of the extended nip (shoe) press was originally focussed on the goal of significantly increasing the solids level to the dryer section for heavy weight grades such as linerboard [1]. Recently, there has been a trend toward use of shoe pressing for printing and writing grades [2-4]. More recently, there have been suggestions that shoe pressing may be advantageous for low basis weight products [5-12]. In this paper, we present results of a laboratory investigation of shoe pressing for low basis weight applications. An abbreviated summary of the work has recently been presented [13].

One of the central issues in the production of low basis weight products is the balance between the need to achieve desired product attributes and the need to attain high levels of productivity. Some of the relevant product attributes are related to sheet bulk. High productivity is closely associated with high levels of sheet solids after the dewatering process. Unfortunately, it is typically difficult to achieve a high solids level without experiencing a penalty in bulk.

[1] (0.73 and 1.72 MPa, simulating 11.9 cm and 5.1 cm shoes, respectively, at a press load of 87.6 kN/m)

At first sight, it may not be obvious that shoe pressing would be advantageous for low basis weight sheets. This is especially true if one considers the typical nip widths (about 10 inches, or 25 cm) associated with current commercial shoe pressing applications for paper/board grades. In the low basis weight realm, the effectiveness of pressing is likely to be far more influenced by peak pressure than by nip residence time (nip width). For the same press load, a long nip would result in peak pressures far lower than those in a typical roll press nip. Thus, for a low basis weight sheet, hypothetically operating in the "compression-controlled" regime of wet pressing, one would expect the longer nips to yield reduced post-nip solids levels. On the other hand, if one allows the nip width to be a design variable, a wide range of peak pressures can be achieved. Furthermore, the shape of the pressure-time pulse can be considered to be available for design optimization [4,14]. In particular, it can be imagined that creation of an unsymmetrical pulse, with the peak shifted toward the exit (expansion) side of the nip, may reduce the time available for rewet. Rewet is expected to play a significant role in pressing of low basis weight sheets. An interaction of the pressure pulse shape and peak pressure magnitude with the resulting sheet bulk would also be expected [11,12].

In contrast to shoe presses, there is no way to cause a conventional roll nip to provide a pulse shape appreciably different from the characteristic, symmetric sinusoidal shape, described by the haversine function in equation (1):

$$p(\tau) = \frac{1}{2} p_{\max}[1 - \cos(\frac{2\pi\tau}{\tau_T})] \qquad (1)$$

In this equation, p is the pressure applied to the web, τ is time (a measure of position in the nip), and τ_T is the total nip residence time. For this pulse shape, the peak pressure ($p_{\max}$) can be shown to be twice the average pressure.

This paper presents results of a laboratory investigation of the following pressing variables: average pressing pressure, pressure-profile shape, nip residence time, and basis weight. It is believed that understanding the effects of these variables will aid in the identification of shoe press designs yielding a desired combination of post-pressing solids and sheet bulk. For a fixed press load, the average pressing pressure can, equivalently, be considered to be a nip width variable. The profile shape parameters include the ratio of peak to average pressure and the relative location of the peak within the nip, and correspond to different amounts of shoe shape and tilt, etc. A control case is included, in which the pressure profile is a haversine function, to simulate a conventional roll nip. Although surface temperature influences pressing, the present study was done at room temperature.

Before presenting the results of the experimental study, we briefly review certain additional terminology relevant to pressing in general, and shoe pressing in particular. We also comment further on the dewatering behavior, and impact on paper properties, to be expected from use of shoe pressing for low basis weight sheets.

REVIEW OF PRESSING TERMINOLOGY AND PARAMETERS

For any press nip, if the nip width is W, and the machine speed is V_m, the total nip residence time is given by:

$$\tau_T = W / V_m \qquad (2)$$

The press (line) load, F' (measured in N/m or pli), is the product of average nip pressure ($\bar{p}$) and nip width:

$$F' = \bar{p} W \qquad (3)$$

A schematic example of a shoe press pulse shape of potential interest in this study is presented in **Figure 1**. The pulse shape is related to the details of the shoe press design [6,8], but this aspect will not be discussed here.

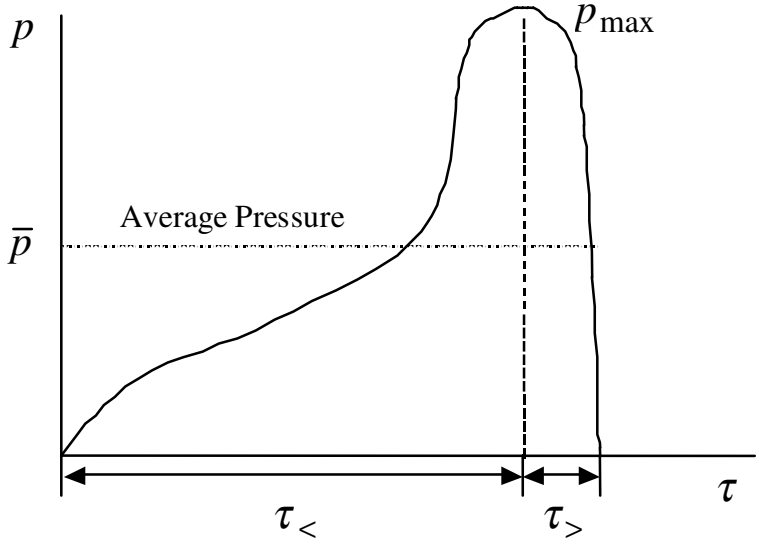

Figure 1. Shoe press pulse shape (pressure vs. time).

While it would be difficult to describe this general shape with a mathematical expression as simple as equation (1), some measures of the general character/severity of the pulse shape can be defined. For example, the peak-to-average pressure ratio is:

$$r_p = p_{\max} / \bar{p} \qquad (4)$$

And, with reference to parameters indicated in Figure 1, the relative peak location is:

$$r_\tau = \tau_> / \tau_T \qquad (5)$$

where:

$$\tau_T = \tau_< + \tau_> \qquad (6)$$

EXPECTED BEHAVIOR

The results to be presented can best be discussed with reference to a set of expected trends derived from generally accepted concepts and theories of wet pressing. First, one would expect that a low basis weight sheet would tend to exhibit compression-, or pressure-controlled behavior, in contrast to the flow-controlled behavior often found for pressing of heavy paper grades. This implies that (if we temporarily disregard rewet effects) the final solids level and caliper should be strongly dependent on the peak applied pressure occurring during the pressing

event, and insensitive to nip residence (dwell) time. With regard to dewatering (and for the case of a fixed press load), a short nip should produce higher solids levels than a long one, due to the higher average pressure. For a given nip width and press load, the most severe shoe pressure pulse shapes (highest peak pressures) should yield higher solids than the flatter ones.

A consideration of rewet in the expansion side of the nip leads to additional expected behavior. First, one would expect that (at equal peak pressure) a shoe press pulse shape similar to that depicted in Figure 1 should yield a higher final solids level than does a roll press (haversine) pulse shape, since there would be less time after the peak for rewet to occur. Furthermore, a higher basis weight sheet would be expected to have a greater final solids than a lighter one, due to a sharing of the rewet water among more fibers.

With regard to the bulk-tensile relationship, one would expect higher peak pressures (created by a short nip and/or severe shoe press pulse shape) to yield lower caliper and higher tensile strength than are yielded by lower peak pressures.

EXPERIMENTAL

Experimental Plan

The experimental plan was to prepare handsheets and press them in a versatile MTS electrohydraulic press, using a number of simulated shoe-press profiles. The pressing conditions selected are listed below. For a press load of 500 pli (87.6 kN/m), the average pressures of 106 and 250 psi (0.73 and 1.72 Mpa) correspond to nip widths of 4.7 and 2 inches (11.9 and 5.1 cm), respectively.

Condition	Value
Platen Surface	Ceramic plated steel
Pulse Shapes	Shoe simulation at 4 levels of Peak/Average Ratio
Dwell	20 and 40 ms
Average Pressures	0.73 and 1.72 MPa (106 and 250 psi)
Platen Temperature	ambient
Basis Weights	13.4 and 24.4 g/m^2 (8.5 and 15 pounds per 3000 ft^2)
Ingoing Solids	~20%
Sheet Preheat	none
Repeats	10 per case
Control (simulated roll press)	Haversine pulse [at 1.72 Mpa (250 psi) average pressure only]

It is recognized that the dwell times listed are appreciably longer than those associated with high-speed machine operation. This limitation was necessary because it is very difficult to program complex pulse shapes of shorter dwell time on the MTS press. The use of two dwell times in the experimental plan is intended as a check on the sensitivity of pressing results to dwell time. Because we expect to be in the pressure-controlled regime, time should be a relatively unimportant variable, although it could certainly have an effect on the amount of rewet.

Experimental Procedures

Sheet preparation. The furnish utilized for the study was a 50/50 blend of Laja pine and Aracruz eucalyptus pulps. The mixture was allowed to soak in water for a few hours and was then disintegrated in a hydropulper. The disintegrated pulp was then refined in a one-pound Valley beater to 498 CSF. Refining was done in roughly 8-minute intervals with freeness tests performed between each interval to determine progress.

After refining, the pulp was diluted t o approximately 0.04% consistency. The stock was diluted to such a low concentration so that a large quantity of handsheets could be made with little deviation in basis weight. Handsheets of two different basis weights were made, 13.4 g/m^2 and 24.4 g/m^2. The process for forming the handsheets followed the method set by TAPPI, T 205 sp-95, with a few changes made. The sheet making procedure (section 7.2 of the method) was followed, but the couching procedure differed from the method. Two standard blotter papers were misted with a spray bottle containing deionized water until damp, but not soaking wet. The damp, smooth side of the moistened blotters was placed face down onto the wet handsheet. Couching was then performed as described in the remainder of the couching procedure (section 7.3 of the method).

After couching and labeling the handsheet, it was lightly misted with the spray bottle and placed on a sheet of plastic film (approximately 4 mils thick) large enough to cover the area of the handsheet. Another piece of plastic film was placed on top of the handsheet to prevent drying. The handsheets were stacked in this manner and then refrigerated until test time.

For MTS testing, each sheet had to be cut into 4" diameter circles. Each handsheet was left between the two pieces of plastic film and die-cut. Keeping the sheets between the plastic films allowed for clean cutting of the lightweight sheet without disturbing its surface fibers against the die press. The plastic film was cut from 8"x 8" heavy-gauge plastic bags. The 4" circle of plastic film remaining on the sheet's felt side was discarded and the sheet (with the plastic film remaining on the wire side) was moistened to 20% solids. The plastic film was left on the wire side so that the sheet would maintain its structure while being handled at such a low solids level.

MTS testing. Figure 2 shows a schematic diagram of the MTS press simulator. Because no preheat was used for this experiment, the heat shield and steaming ring shown were not used. The top platen (unheated) was mild steel with a ceramic surface coating. The bottom platen (unheated) had a piece of blind-drilled shoe press blanket epoxied to a 3/4-inch thick steel plate. This platen was placed on the pedestal and shimmed so that both platens were parallel.

Four-inch diameter samples were cut from a new press felt for use in the experiments. Before testing, the felts were preconditioned by soaking in deionized water until they were saturated, stacked with a steel plate between each felt and an unvented platen on the bottom and top, and cycled 1000 times between ~110 and ~870 psi at a frequency of 3Hz. The felts were then resoaked, restacked in reverse order and pressed for an additional 1000 cycles. This was repeated ten times for a total of 10,000 cycles.

To prepare the felts for pressing experiments, they were again soaked until saturated, placed between fresh blotters (two on the top and two on the bottom) and then pressed with a British couch roll for a total of ten back-and-forth passes. This resulted in felt moistures between 33 and

35%. For all MTS tests, the felts were aligned so that the MD direction was the same as the MD direction of the blanket.

After a sheet was pressed in the MTS, it was weighed, finish-dried in a laboratory dryer (followed by oven drying) and weighed again to allow calculation of final solids content. The dry samples were used for measurement of caliper and tensile strength.

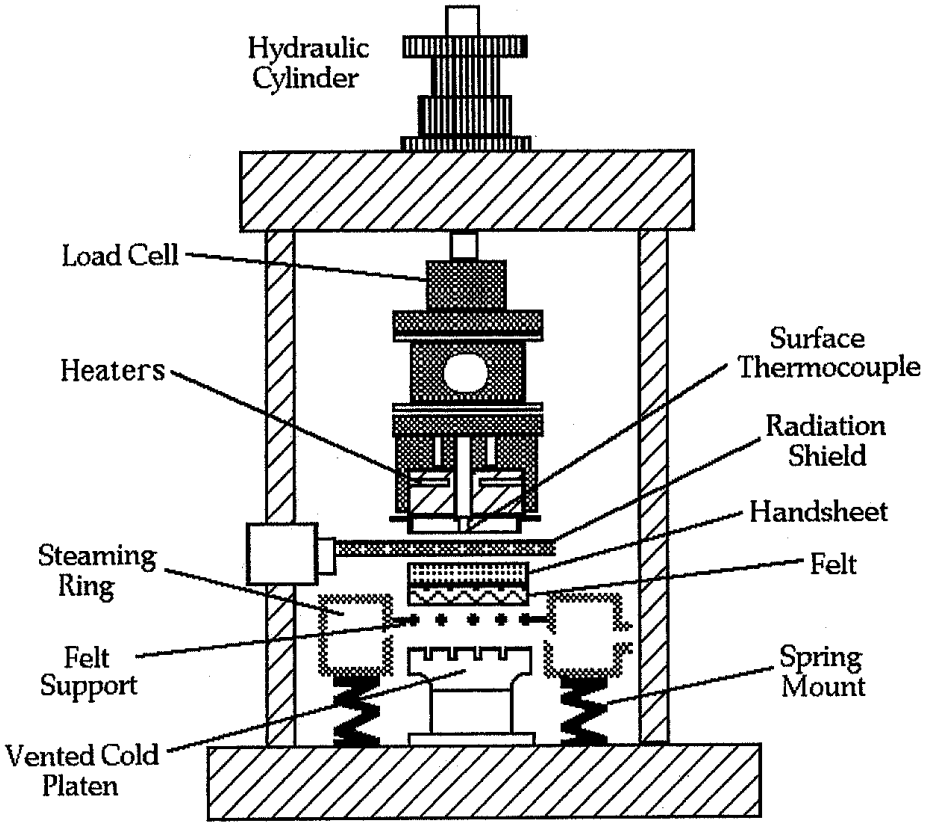

Figure 2. The IPST laboratory press simulator.

RESULTS AND DISCUSSION

Pressure Profiles

The 20 ms pressure pulses were programmed first. The 40 ms pulses were then programmed to have a shape as close to the 20 ms pulses as possible, to ensure that the only variable between corresponding sets was dwell time. **Figures 3–6** show typical pressure pulses, for the 20 ms and 40 ms cases, measured during the experiments.

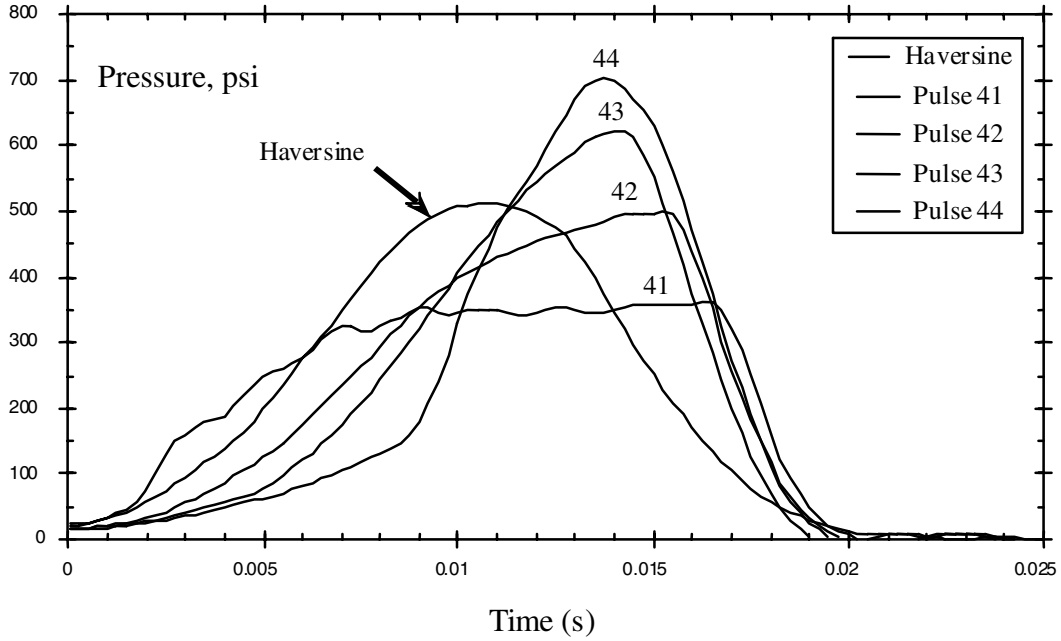

Figure 3. Typical 20 ms pulses: high average pressure (short nip).

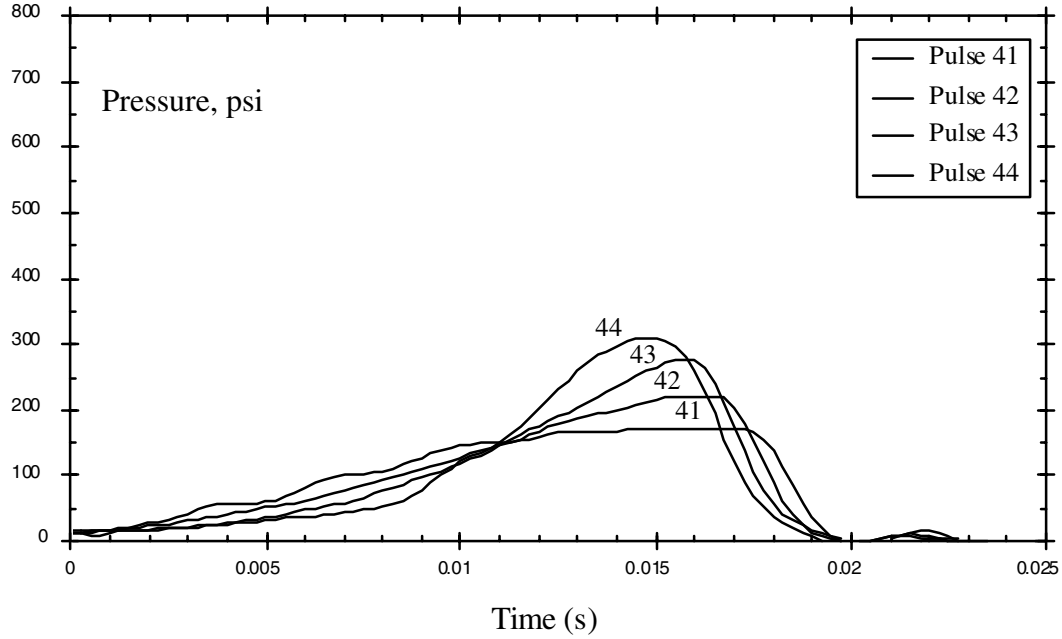

Figure 4. Typical 20 ms Pulses: low average pressure (long nip).

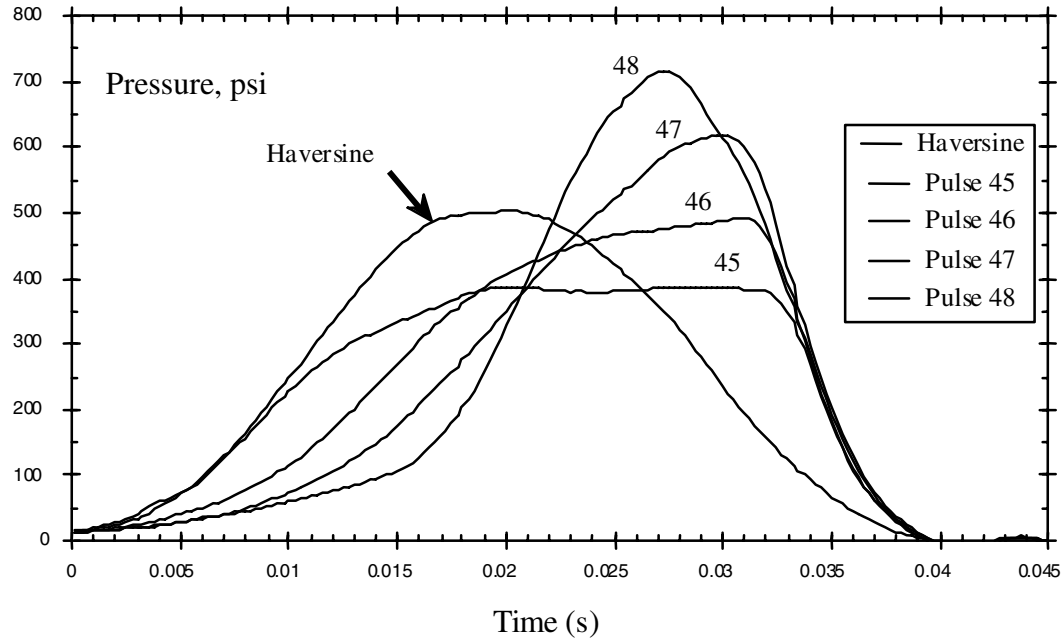

Figure 5. Typical 40 ms Pulses: high average pressure (short nip).

For readers who prefer SI units for pressure, let it be noted that 1 psi is equivalent to 6.895 kPa.

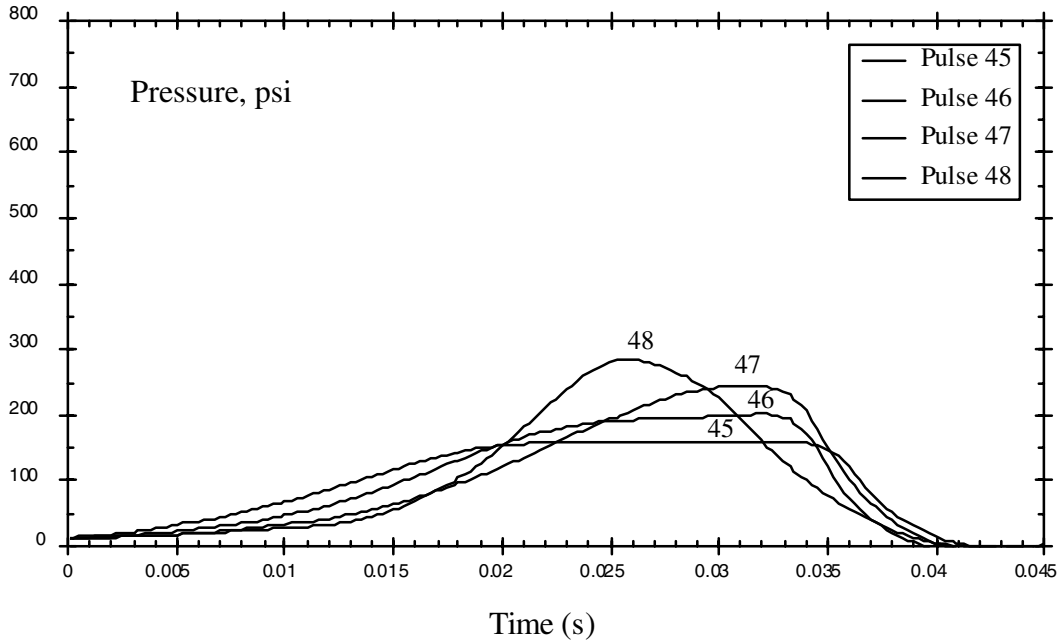

Figure 6. Typical 40 ms Pulses: low average pressure (long nip).

It was not feasible to program all the shoe press pulses to have the same relative peak location (r_τ), as defined in equation (5) and Figure 1. The approximate values of r_τ and r_p (see equation 4) are given in **Table 1**. The variation in this parameter will be considered in discussing the dewatering results later in the paper.

Pulse Program	Nip width[a] (cm)	Average Pressure (MPa)	Dwell Time (ms)	Peak-to-Average Pressure Ratio (r_p)	Relative Peak Location (r_τ)
Haversine	5.1	1.72	20	2	0.50
41	5.1	1.72	20	1.42	0.165
42	5.1	1.72	20	2	0.23
43	5.1	1.72	20	2.48	0.29
44	5.1	1.72	20	2.8	0.31
41	11.9	0.73	20	1.56	0.145
42	11.9	0.73	20	2.03	0.175
43	11.9	0.73	20	2.59	0.21
44	11.9	0.73	20	2.88	0.26
Haversine	5.1	1.72	40	2	0.50
45	5.1	1.72	40	1.52	0.20
46	5.1	1.72	40	1.94	0.22
47	5.1	1.72	40	2.46	0.25
48	5.1	1.72	40	2.84	0.32
45	11.9	0.73	40	1.42	0.145
46	11.9	0.73	40	1.89	0.185
47	11.9	0.73	40	2.26	0.21
48	11.9	0.73	40	2.59	0.355
(a) assumes press load is 500 pli (87.6 kN/m)					

Table 1. Pressure pulse characteristics.

Water Removal

The water removal results for the various pulses studied (see Figures 3-6 and Table 1) are shown in **Figures 7** and **8**. The error bars represent 95% confidence intervals [15]. In **Figures 9** and **10**, the final solids levels are presented as a function of the peak pressures occurring during these pulses, since we expect peak pressure to be a significant parameter for pressing of low basis weight sheets.

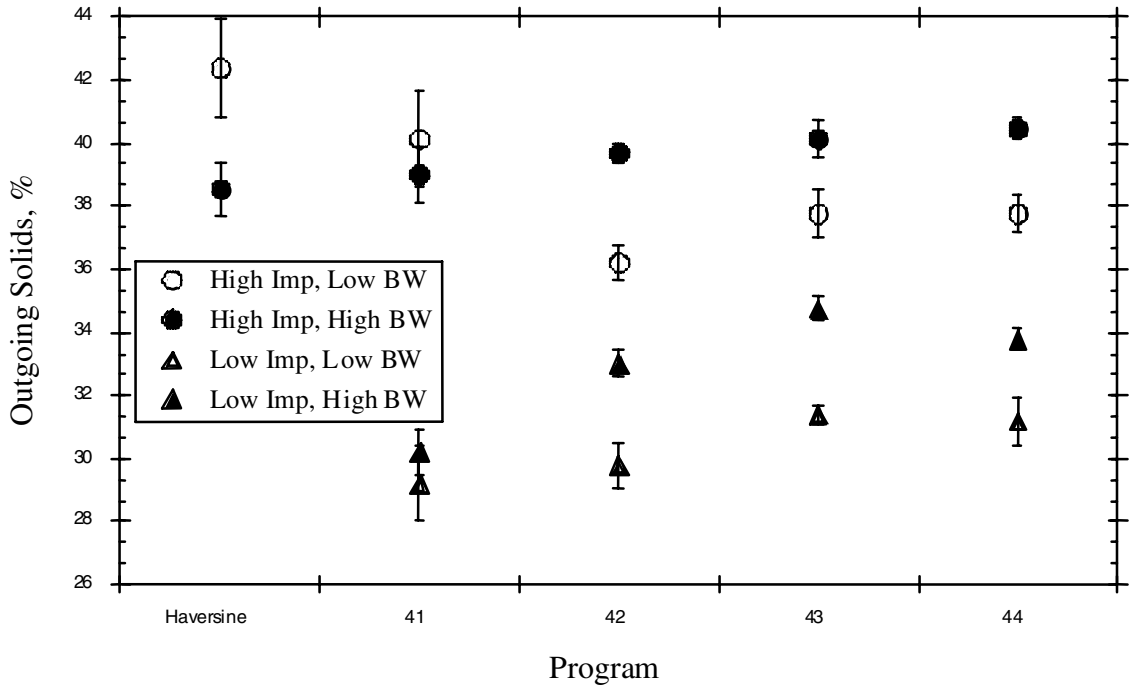

Figure 7. Outgoing solids for 20ms pulses. [Imp = Impulse, proportional to average pressure].

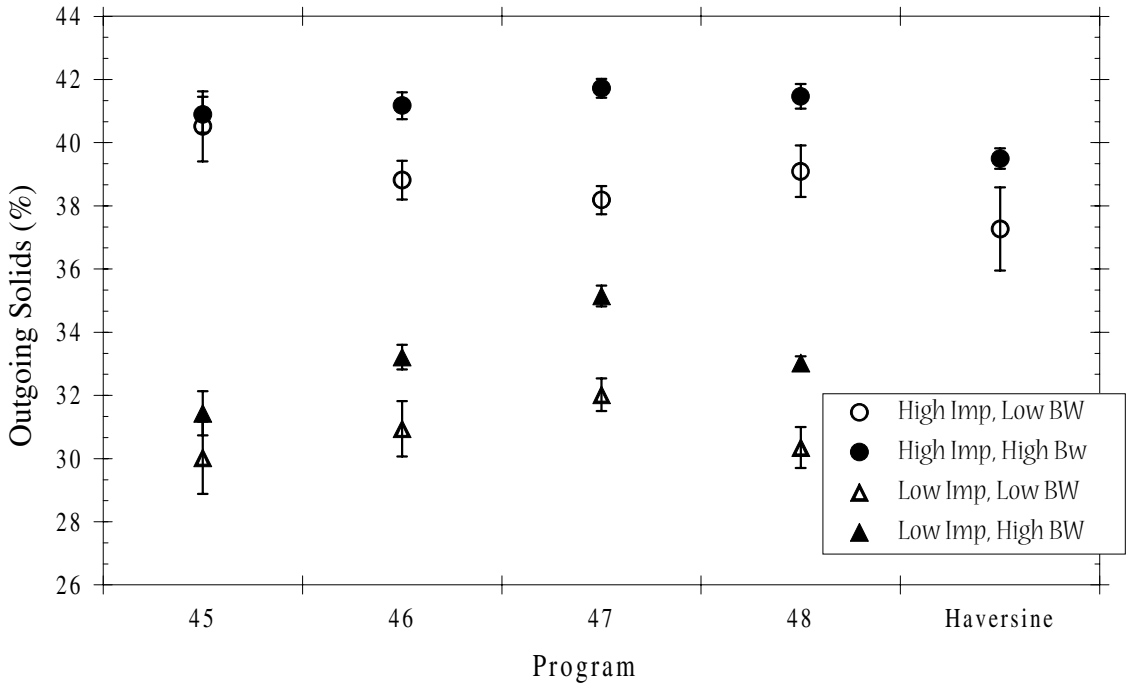

Figure 8. Outgoing solids for 40ms pulses. [Imp = Impulse, proportional to average pressure].

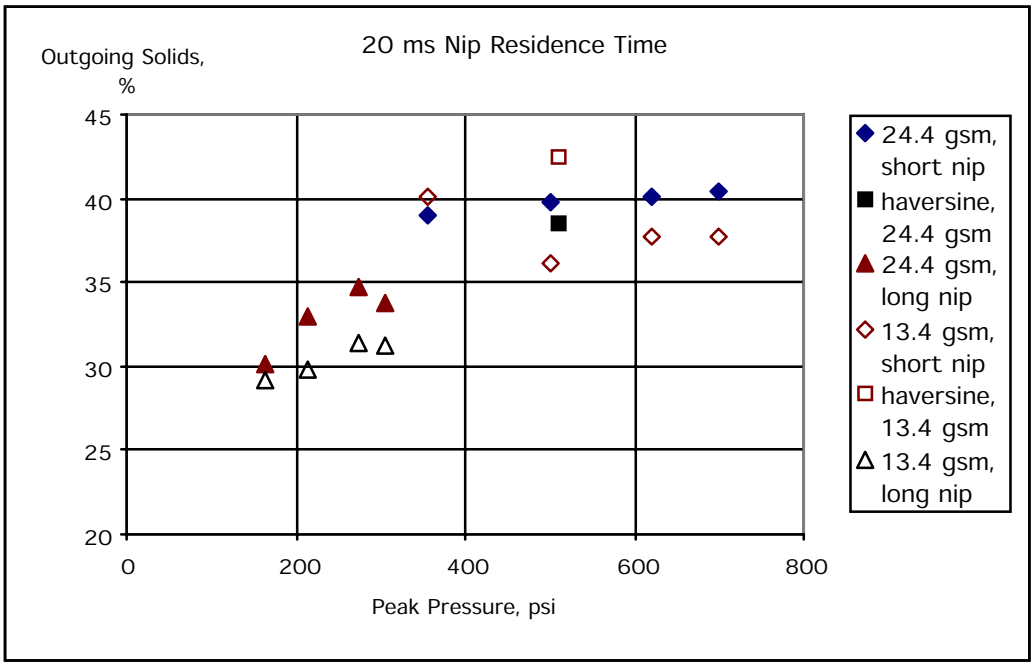

Figure 9. Outgoing sheet solids for pulses studied, at 20 ms dwell.

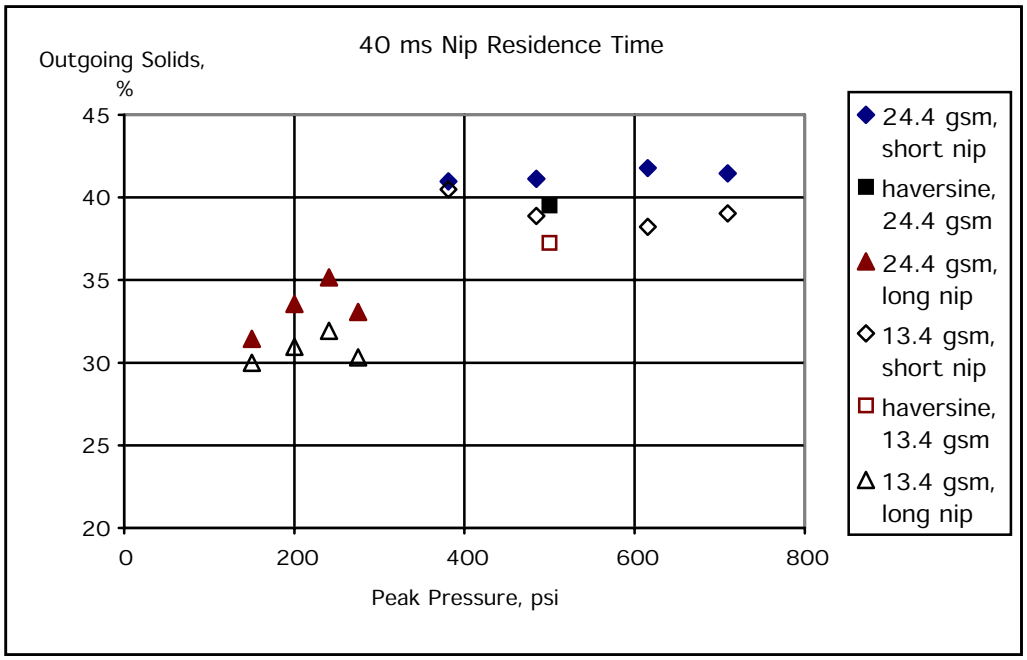

Figure 10. Outgoing sheet solids for pulses studied, at 40 ms dwell.

The solids data presented in Figures 7-10 reasonably support the expected trends stated earlier in the paper. In particular, considering the optimum solids condition for each combination of nip width and basis weight:

- The short shoe (high average pressure) tended to yield about a 6 percentage-points solids benefit at high basis weight compared to the long shoe (low average pressure) case. At lower basis weight the solids benefit was still greater, about 8.5 percentage-points. This was true for each dwell time.

- The high basis weight final solids level was nearly one percentage-point higher for the short shoe and about three percentage-points higher for the long shoe, compared to the corresponding low basis weight cases. This was true for each dwell time.

Some additional observations concerning the dewatering results are as follows:

- Dwell time had a rather small effect, but longer time yielded a slightly higher (about 1/2 percentage point) solids level. This could be due to viscoelastic effects. Since, at a given average pressure, the press impulse at 40 ms is twice that at 20 ms, the minor effect of impulse on dewatering further supports the claim that the pressing conditions studied behave in a way compatible with the pressure-controlled model. A strong dependence on impulse is normally associated with the "flow-controlled" regime (typically encountered when pressing high basis weight sheets).

- With the exception of the short nip, low basis weight cases, the greatest solids level occurred when using the narrow shoe press pulse shapes with the steeper depressurization (high r_p). The reason for the exception is not entirely clear, but could be related to the fact that these

cases had the lowest relative peak location (r_τ) values (see Table 1) and, thus, were minimally influenced by rewet effects.

- The fact that, for the long nip cases, the highest solids did not occur at the highest peak pressure is likely explained by the fact that these runs had comparatively large values of r_τ and, thus, were impacted more than others by rewet effects.

- In three of the four cases in which the haversine pulse and a shoe pulse at equal peak pressure were compared, the shoe pulse yielded a higher solids level. This is expected based on the rewet (relative peak location) argument presented earlier. The reason for the exception (at 20 ms dwell and low basis weight) is not clear.

- For the high basis weight cases, at both dwell times, all shoe press pulses with average pressure equal to that of the haversine pulse yielded better dewatering than the haversine pulse

Physical Properties

Since it was expected that the pressure profile shape and peak pressure could influence bulk and strength, as well as water removal, the caliper and tensile strength of each sample was measured. **Tables 2** and **3** contain the results of these measurements, for the 20 ms and 40 ms dwell cases, respectively, together with the final sheet solids data (for convenient reference). It should be noted that the caliper and tensile values represent uncreped sheets, so care should be exercised in interpreting these data.

The caliper and tensile data are reasonably compatible with the expected behavior, although perhaps not as consistently so as was the case for the dewatering data. For example, for the pulses that gave the best final solids (at fixed width, basis weight and dwell), the caliper tended to be least. Furthermore, considering all the data, the conditions yielding higher caliper tended to yield lower tensile strength, and vice versa. Therefore, for conditions exhibiting higher sheet solids, lower caliper, and higher sheet strength, the furnish strength can be lowered by refining less, hence allowing a tradeoff of strength for caliper, ultimately leading to even better sheet solids.

Since tradeoffs between dewatering and bulk are often of interest, the effect of the final solids level on sheet (uncreped) caliper is presented in **Figures 11** and **12**, for the 24.4 g/m^2 cases. It can be seen that the flattest shoe pulses produced as good, or better, caliper than the haversine, while achieving better dewatering. In fact, for the 20 ms cases, three of the four shoe pulses yielded as good, or better, caliper than the haversine. The reason that the data points for pulses 44 (Figure 11) and 48 (Figure 12) appear to be out of order is likely the result of poorer than expected dewatering, associated with the comparatively large relative peak location values for these pulses.

Nominal Impulse (psi·sec)	Nip Width At 500 pli (inches/cm)	Basis Weight (g/m^2)	Press Program	Uncreped Caliper[a] (mils/sht)	Tensile[b] (g/3-inch)	Outgoing Solids (%)
5	2/5.1	24.4	Haversine	3.22	2139	38.5
			Shoe: 41	3.52	1940	39.0
			42	3.25	2119	39.7
			43	3.03	2217	40.1
			44	3.24	2224	40.4
5	2/5.1	13.4	Haversine	2.41	819	42.4
			Shoe: 41	2.49	803	40.1
			42	2.49	833	36.2
			43	2.44	789	37.7
			44	2.49	864	37.7
2.1	4.7/11.9	24.4	Shoe: 41	3.62	1899	30.2
			42	3.75	1849	33.0
			43	3.41	1977	34.7
			44	3.59	1965	33.8
2.1	4.7/11.9	13.4	Shoe: 41	2.60	691	29.2
			42	2.62	747	29.8
			43	2.58	730	31.4
			44	2.53	781	31.2

Notes: (a) caliper is in mils/sheet; 1 mil = 25.4 μm.
(b) Tensile is in grams/ 3-inch wide sample.

Table 2. Summary of key results for 20 ms dwell time.

Nominal Impulse (psi·sec)	Nip Width At 500 pli (inches/cm)	Basis Weight (g/m^2)	Press Program	Uncreped Caliper[a] (mils/sht)	Tensile[b] (g/3-inch)	Outgoing Solids (%)
5	2/5.1	24.4	Haversine	3.21	2349	39.5
			Shoe: 45	3.20	2043	40.9
			46	3.12	2334	41.2
			47	3.02	2468	41.7
			48	3.11	2353	41.5
5	2/5.1	13.4	Haversine	2.57	794	37.3
			Shoe: 45	2.25	833	40.5
			46	2.32	862	38.8
			47	2.26	882	38.2
			48	2.48	831	39.1
2.1	4.7/11.9	24.4	Shoe: 45	3.52	2058	31.4
			46	3.44	2040	33.6
			47	3.20	2370	35.2
			48	3.36	2105	33.0
2.1	4.7/11.9	13.4	Shoe: 45	2.47	789	30.0
			46	2.44	862	30.9
			47	2.46	805	32.0
			48	2.62	686	30.4

Notes: (a) caliper is in mils/sheet; 1 mil = 25.4 μm.
(b) Tensile is in grams/ 3-inch wide sample.

Table 3. Summary of key results for 40 ms dwell time.

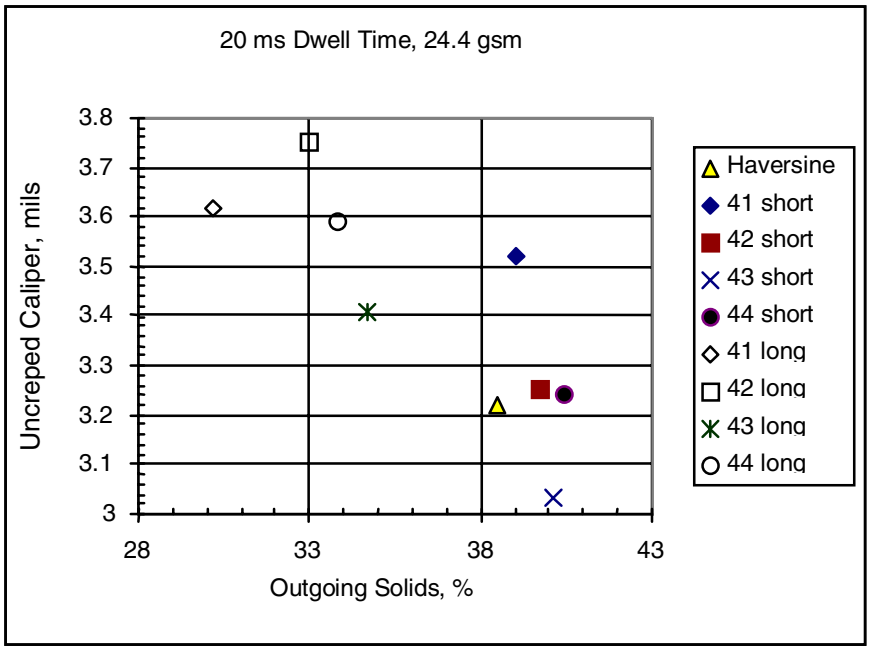

Figure 11. Variation of uncreped caliper with outgoing solids, for 20 ms pulses.

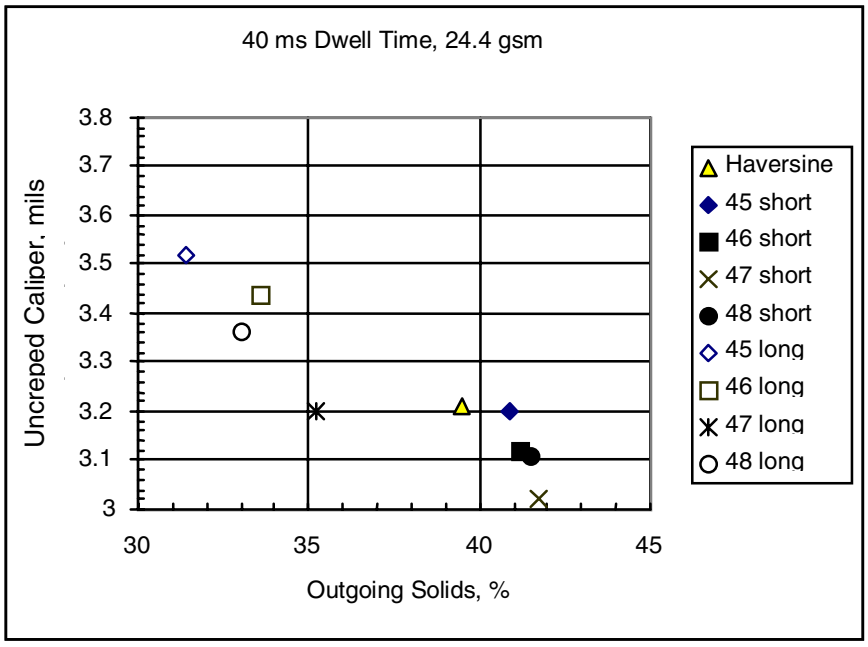

Figure 12. Variation of uncreped caliper with outgoing solids, for 40 ms pulses.

CONCLUDING REMARKS

The shoe pressing study presented here, while having some limitations, was successful in demonstrating that shoe press nip length and pulse shape can be adjusted to achieve improvements in dewatering and/or bulk, compared to roll presses, for low basis weight sheets. The experimental conditions specified in the original experimental plan were all achieved. The following points are considered particularly noteworthy:

- The expected trends (based on a pressure-controlled pressing regime point-of-view) were verified by the experimental results most of the time.
- The dewatering benefit of narrow, high peak-to-average pressure shoe press pulses (compared to a roll nip pulse) appears to be mainly the result of reduced rewet, but with a significant contribution from the higher peak pressure, as well. The reduced rewet is attributed to the shift of the peak pressure toward the exit side of the nip. The contribution of high peak pressure was found to be greater for the long nip than for the short nip.
- The use of ten repeats per experimental condition was advantageous for achieving low variability in the dewatering results.

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