PRELIMINARY HOT PRESSING INVESTIGATION

Project F002

Report 5

to the

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

May 1998

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

Atlanta, Georgia

PRELIMINARY HOT PRESSING INVESTIGATION

Project F002

Report 5

A Progress Report

to the

MEMBER COMPANIES OF THE INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

By

T.F. Patterson and I. Rudman

May 1998

Table of Contents

F002 Report: Preliminary Hot Pressing Investigation

1. Summary

This work was initiated to investigate the interaction between web temperature profile, web moisture profile, and water removal and final sheet mechanical properties. In an initial set of experiments (Pressing of Heated Sheets - First MTS Experiments (summer 1996)), the effect of ingoing consistency (solids) and ingoing temperature were investigated using a pressure pulse which was not varied with sample solids content. Ingoing sheet temperature was varied by steaming. Additionally, the effect of ingoing solids and temperature on the compression and permeability of the wet paper were measured. With no attempt to optimize the pressure profile, the results indicated that:

1. Increasing sheet temperature by steaming did not necessarily increase the water removal and mechanical strength;

2. The moisture profile of the steamed sheet may affect water removal and mechanical strength of the sheet.

A summary of this work is given in Appendix B.

Based on these observations, it was decided to examine how preheating methods, which change the sheet moisture profile, effect the pressing response of sheets at different ingoing solids and sheet temperatures. Specific areas of interest were water removal, final mechanical strength, and sheet compression. An attempt was made to tailor the pressing pulse to the solids content of the sample. The results of the research indicated that moisture profile and ingoing sheet temperature are significant factors governing water removal and development of mechanical strength.

The work was conducted in two phases:

1. Single-stage pressing of sheets with ingoing solids of 25% and 45%. This entailed preheating the sheet by one of two means, pressing the sheet, drying the sheet under constraint, conditioning the sheet and then measuring soft platen caliper, specific elastic modulus, CD STFI Compression, and MD STFI Compression. Two types of sheets were used: one consisted of three layers of equal basis weight which had a combined basis weight of 205 gsm and the other was a single layer sheet with a total basis weight of 205 gsm. The multi-layer samples were only tested at 25% solids. This work provided information on temperature and moisture profile and the relative effect of those parameters.

2. Three-stage pressing of sheets with an initial ingoing solids of 25%. This entailed measuring the sheet caliper, preheating the sheet, pressing the sheet, and measuring the sheet caliper. This was done three times, each successive pressing used a higher impulse. The samples were heated to approximately

the same temperature prior to each pressing and, except for the first pressing, no attempt was made to regulate ingoing solids. After the third pressing, the sheet was dried under constraint, and measurements were made of soft platen caliper, specific elastic modulus, CD STFI, and MD STFI. This work provided information on the maximum attainable benefits of a particular means of heating.

The testing produced a number of interesting findings:

1. Water removal is a function of sheet moisture profile and sheet temperature.
2. Sheet solids content modifies the effect of sheet moisture profile on water removal.
3. Final sheet properties can be a function of sheet moisture profile, sheet temperature, and sheet solids.
4. Water removal is non uniform in the z-direction, water removal in the bottom portion of the sheet is greater than in the top portion of the sheet.
5. A pressing pulse of insufficient magnitude used in combination with web heating can result in no increase in water removal.

2. Sheet Preparation and Experimental Plan

The current experiments were conducted using the same furnish as was used in the experiment documented in Appendix A. The 205 g/m^2 ($42\#/1000ft^2$) sheets used were made on the Formette Dynamique Sheet Former from 616 ml CSF OCC pulp. They were formed and dewatered at a speed of 1800 m/min. After light prepressing at the Baldwin Press to solids 25%, one half of all the sheets were then prepressed on a laboratory roll-press to a solids content of 45%. Each 889 mm x 216 mm (35 in x 8.5 in) Formette sheet was die cut to make 76.2 mm x 63.5 mm (3 in x 2.5 in) samples having both MD and CD orientations.

The 68.3 g/m^2 ($14\#/1000ft^2$) sheets used for the layered samples were also made on the Formette Dynamique Sheet Former from the same 616 ml CSF OCC pulp. They were formed and dewatered at a speed of 800 m/min. The lower speed was required to obtain satisfactory uniformity. The sheets were prepressed to 25% solids. Each 889 mm x 216 mm (35 in x 8.5 in) Formette sheet was die cut to make 76.2 mm x 63.5 mm (3 in x 2.5 in) samples having both MD and CD orientations.

Table 2.1 shows the experimental matrix for the pressing performed on the single-layer, full-basis-weight sheets. The work was performed using a laboratory-scale electrohydraulic platen press (MTS press) which is able to simulate various nip pressure profiles. There was some variation in the pressing pulse because of changing solids content, sheet temperature, and some slight variations in basis weight. Only single-felted pressing was performed. A ceramic-coated platen was mounted in the press, this surface contacted the sheet during pressing. Pressing was carried out at a constant platen temperature of 60°C. Temperature and pressure were recorded during the pressing pulse.

Steam heating was accomplished using a steaming ring which surrounded the lower platen of the press. The ring had a series of holes around its inside diameter, from which the steam was emitted. The emitted steam had a low velocity and was generally, although not completely, directed at the top of the sheet. The sheet rested on the felt during steaming. Immediately after steaming the sheet was pressed. There was a delay of 2-5 seconds, between steaming and pressing, imposed by the limitations of the MTS.

Plate heating was accomplished using a thin heating blanket attached to a rigid surface. The heater temperature was controlled to within 1°C of the desired temperature. The blanket was oriented with the hot surface facing upward. The sheet top side was placed against this surface, its bottom side facing upward. The top side of the felt was placed against the bottom side of the sheet. A lightweight ceramic plate was then placed against the bottom side of the felt. Thus, the sheet and felt were heated together in an upside down orientation. During heating the upper and lower surfaces of the sheet and felt assembly were covered with a high temperature plastic sheet to limit evaporation. At the end of a predetermined heating time the sample and felt were quickly placed in the press. There was a time delay of approximately 5-8 seconds, between completion of heating and pressing.

Test	Sheet Type	Ingoing Solids %	Heat	Avg. Ingoing Temp.	Press Impulse (psi-sec)	Peak Pressure (psi)	Impulse Duration	Impulse Shape
Single-stage	Layered	25	none	25°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Layered	25	steam	59°C	7.2-8.3	700-940	20 ms	haversine
Single-stage[1]	Layered	25	steam	60°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	25	none	25°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	25	steam	59°C	7.2-8.3	700-940	20 ms	haversine
Single-stage[1]	Whole	25	steam	60°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	25	steam	73°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	25	steam	88°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	25	plate	58°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	25	plate	77°C	7.2-8.3	700-940	20 ms	haversine
Single-stage	Whole	45	none	25°C	9.2-9.6	1080-1110	20 ms	haversine
Single-stage	Whole	45	steam	49°C	9.2-9.6	1080-1110	20 ms	haversine
Single-stage	Whole	45	steam	92°C	9.2-9.6	1080-1110	20 ms	haversine
Single-stage	Whole	45	plate	58°C	9.2-9.6	1080-1110	20 ms	haversine
Single-stage	Whole	45	plate	83°C	9.2-9.6	1080-1110	20 ms	haversine
Three-stage	Whole	25	steam	45-50°C	7.2-8.3	700-940	20 ms	haversine
					9.2-9.6	1080-1110 1300-1600	20 ms	haversine
					30-40		40 ms	shoe
Three-stage	Whole	25	plate	58°C	7.2-8.3	700-940	20 ms	haversine
					9.2-9.6	1080-1110 1300-1600	20 ms	haversine
					30-40		40 ms	shoe

Table 2.1. Experimental Matrix

[1] Steam heated for 40 seconds, allowed to cool for 200 seconds.

3. Weight and Heating Calibration

3.1 Steam Preheating

Since the ingoing temperature of the wet-pressed sheet was a variable, experiments were conducted to identify the heating time required to preheat the sheet to various ingoing temperatures. To this end, sheets with embedded thermocouples were prepressed to solids contents of 25% and 45% and used for a steaming temperature calibration. The sheets were five-ply. Each layer was 41 g/m^2 for a combined basis weight of 205 g/m^2. Thus, each sheet could have employed six thermocouples, four embedded in the sheet, one on the top, and one on the bottom. Since the data acquisition system could record data from only four thermocouples, the thermocouples were positioned as follows:

1st thermocouple, T_1, $z = 0.0\,L$

2nd thermocouple, T_2, $z = 0.4\,L$

3rd thermocouple, T_3, $z = 0.6\,L$

4th thermocouple, T_4, $z = 1.0\,L$,

where L is the thickness of the sheet and $z = 0$ is the interface between the sheet and the felt. The average temperature of the sheet, T_{av}, was calculated as a weighted mean:

$$T_{av} = 0.2\,(T_1 + T_2) + 0.1\,(T_2 + T_3) + 0.2\,(T_3 + T_4).$$

It is important to note that the steam did not impinge on the surface of the sheet at high velocity. Rather, the sheet was steamed with a low speed and somewhat unordered flow. The temperature of the steam near the surface of the sheet was about 100°C. It was expected that prevailing mechanism of heat transfer would be through steam condensation while convection would be minimal.

The sheets were placed on top of a felt (16% moisture content), were steamed for 40-seconds, then the steam was shut off and the sheet was allowed to cool off for 200-seconds. The temperature response was recorded and average temperatures were calculated. The average temperature responses for sheets steamed at ingoing solids 25 and 45% are shown in Figure 3.1.

The temperature of the steamed sheet leveled off after 40-seconds steaming. The steaming curve had an ascending part (steaming during the first 40 seconds) and a descending part (steam is shut off and the sheet cooled off to ambient temperature). Observations showed that the same ingoing temperature could be reached in either of two ways:

- steaming for a specific time corresponding to the selected temperature on the ascending portion of the curve;
- steaming for 40-seconds and subsequent cooling-off over a specific time.

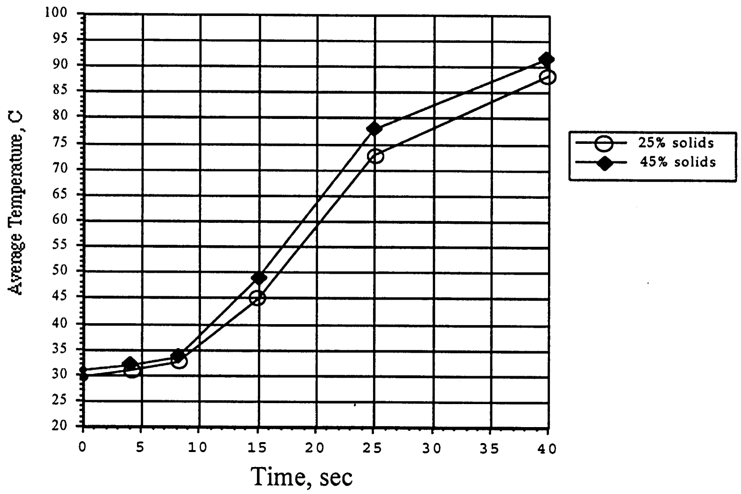


Figure 3.1. Average Sheet Temperature vs. Steaming Time

The ascending part of steaming curve is characterized by a steep temperature profile (difference in temperature through the sheet was up to 30-40°C). This profile decreases somewhat between the end of steaming and the beginning of pressing.

The amount of water gained during the steam calibration was determined for different steaming times at ingoing solids of 25% and 45%. The results are tabulated in Table 3.1. Increasing solids resulted in decreasing weight gain. Based on the weight gained data, a condensation curve was calculated and plotted in Figure 3.2.

	Steaming Time, (sec)				
	4	8	15	25	40
Gained Water at 25% Solids, (g)	0.0786	0.1278	0.1582	0.1684	0.1892
Rate of Gain (g/m^2)	16.24	26.41	32.69	34.80	39.10
Average Temperature (°C)	29	32	45	73	88
Gained Water at 45% solids, (g)	0.0666	0.0674	0.072	0.0666	0.0636
Rate of Gain (g/m^2)	13.76	13.93	14.88	13.76	13.14
Average Temperature (°C)	31	33	49	78	92

Table 3.1. Steam Heating Calibration

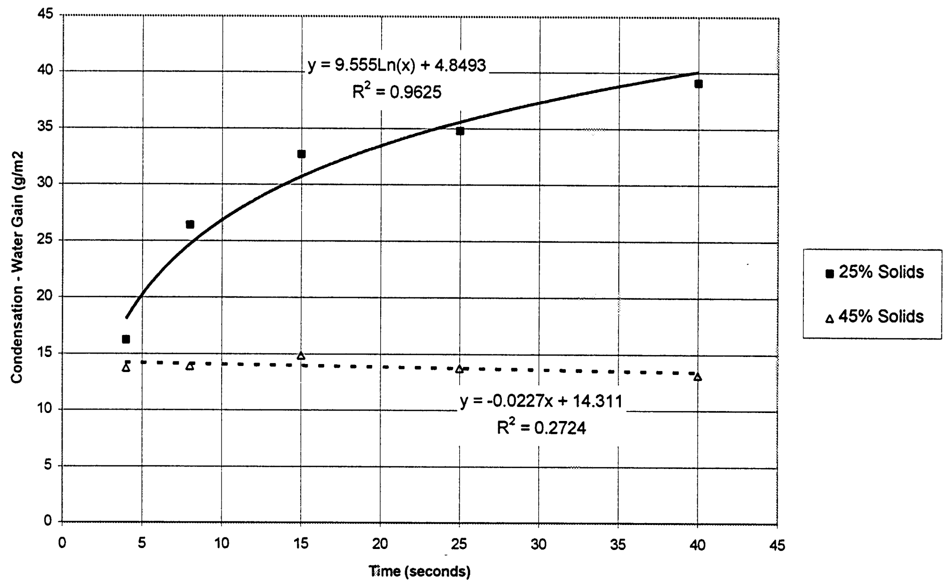


Figure 3.2. Condensation/Area vs. Steaming Time

Experiments conducted on the Steambox Comparator [1] to simulate steaming at commercial conditions (speed - 2000 fpm, steam flow rate - 0.096 kg steam/kg fibers) produced a water gain of 30 g/m^2 at a vacuum level of 7 in Hg and sheet solids of 25%. This water gain decreases the ingoing solids to 24.1%. As is seen from the condensation curve, the gain is similar to the water gained during 15-second steaming on the MTS. Average temperatures of the sheets when steaming on the Steambox Comparator and MTS press were also close, about 45-50°C. However, the dwell time on the steam box comparator was about 20-40 ms, thus the condensation rates were significantly higher.

3.2 Plate Preheating

A temperature weight calibration was also conducted for plate heating. It was intended to reach the same temperatures as in the case of steaming. The temperature controller was set to maintain the surface temperature of the plate at 65°C and 95°C in order to obtain average sheet temperature ~60°C and ~80°C, respectively. To ensure faster heating through of the sheet, the sheet was lightly pressed against the heated plate with a pressure of 827 Pa (0.12 psi). Heating times were limited to avoid excessive drying out of the sheet surface which faced the heater. The data for selected heating times are tabulated in Table 3.2.

Plate Temperature	Ingoing Solids	Average Sheet Temperature	Preheating Time (sec)	Water Loss, (g)	Apparent Compression, %
95.0 °C	25%	77.0°C	20	0.168	2.23
65.0 °C	25%	58.3°C	25	0.094	0.702
95.0 °C	45%	83.0°C	25	0.141	3.576
65.0 °C	45%	58.0°C	25	0.079	2.879

Table 3.2. Plate Heating Calibration

4. Heating and Pressing of Layered Sheets

4.1 Introduction

As a complement to the single-stage pressing, three layer samples with a total basis weight of 205 g/m^2 were prepared, heated, and pressed at selected single-stage pressing conditions. Each layer had the same basis weight, 68.3 g/m^2, one third of the total. This was done primarily to obtain a clearer picture of the sheet moisture profile before and after pressing. Some information was also obtained on sheet strength.

4.2 Experimental Procedure

The layered sheets were used to examine the effects of both preheating and pressing. In the case of preheating, the objective was to determine the moisture profile of the sheet immediately after preheating. In the case of pressing, the objective was to determine the moisture profile immediately after pressing. The three layered sheets were preheated in the same manner as the whole sheets, (i.e., steam and hot plate). Accurate weight measurement required that incidental moisture losses be minimized. These losses would occur primarily through evaporation since the sheet was at an elevated temperature. Post-preheating and post-pressing weighing of the samples were conducted as quickly as possible. To diminish the effect of weighing on the moisture profile results, it was conducted in alternating order, that is, in half of the measurements the top layer was weighed first, while in another half, the bottom layer was weighed first. Two balances were used to further reduce the time required to perform the weighing. The procedure was as follows. A piece of plastic was placed on the top of the sample and another piece was placed on the bottom of the sample. The top (bottom) layer was peeled off and placed on the first scale with the top piece of plastic covering the layer. The weight was recorded. The bottom (top) layer was peeled off and placed on the second scale with the bottom piece of plastic covering the layer. The weight was recorded. The middle layer was placed on the first scale with a third piece of plastic on top of it. The top (bottom) layer was not removed from the scale prior to weighing the middle layer, this eliminated the need to wipe any moisture from the scale surface. The middle layer weight was obtained by subtracting the weight of the first layer placed on the scale from the total weight of both layers placed on the scale. After obtaining the weights of the three layers, a coarse moisture profile could be constructed.

4.3 Weight Gain Calibration - Preheating

The results of the weight gain calibration for steam and hot plate preheating are presented in Table 4.1. The table shows the water gain for each layer as well as for the entire layered sheet (sum of layer weight gains) and for a similar single-ply sheet of the same total basis weight.

The following conclusions can be derived from the results of the weight-gain calibration:

1. Water gain/loss for the layered preheated sheets was significantly higher than that for the whole sheets. It is believed that the main reason for this is that the

layered sheets were not pre-pressed, but stacked. This possibly provided an in-plane path for vapor to enter or leave the sheet. The sheets could not be pre-pressed, since separation of the layers would take much more time than for the stacked sheet which would result in significant error when measuring water gain/loss.

2. Water gain/loss in the top layer was higher than for the middle. Except in the 45% solids, 15-second steaming case, water gain/loss for the middle layer was greater than that for the bottom layer. Steam heating produced a moisture profile that went from wetter on the top to dryer on the bottom of the sheet. Plate heating produced the opposite profile, dryer on the top and wetter on the bottom. Given that the total moisture absorbed by the layered and the whole sheets followed the same trend, it is reasonable to expect that the whole sheet will have the same trend in moisture profile.

3. The 40-second steaming/200-second waiting case produced less water gain than the 40-second steaming case. It also produced a shallower moisture gradient than either of the 25% solids cases. This suggests that some moisture evaporated off the exposed top surface and that some moisture diffused towards the bottom of the sheet.

	Water Gain (g)				
	Layered Sheet			Entire	Entire
	Top Layer	Middle Layer	Bottom Layer	Layered Sheet	Standard Sheet
25% 20 sec steam (59°C)	0.091	0.064	0.056	0.211	0.163
25% 40 sec steam (88°C)	0.114	0.066	0.061	0.284	0.189
25% 40 sec steam, 200 sec wait (60°C)	0.081	0.069	0.057	0.207	0.098
25% Plate heating (65°C)	-0.066	-0.035	-0.028	-0.129	-0.094
45% 15 sec steam (49°C)	0.037	0.027	0.028	0.092	0.072
45% Plate heating (65°C)	-0.173	0.013	0.070	0.090	0.079

Table 4.1 Water Gain During Preheating

Overall, the results of the weight calibration confirmed the hypothesis that preheating changes moisture profile. At the same time it should be recognized that accurate measurement of the moisture profile is very difficult. Based on the results of this experiment, it seems that future measurements of moisture profile should use only two-layered sheets. Multiple tests made with layers of different basis weights would be required to determine the moisture profile.

4.4 Results of MTS Pressing

The layered-sheet pressing results, including percent increase in dryness, conditioned density, and conditioned specific elastic modulus (SEM) are shown in Figure 4.1,Figure

4.2, andFigure 4.3. A number of interesting trends can be observed. Figure 4.1 shows quite clearly that under all measured pressing conditions, water removal is greatest in the bottom layer and least in the top layer. A compensating factor may be the significantly greater permeability of the felt as compared to the sheet. The result also suggests that if the bottom of the sheet could be heated, instead of the top of the sheet, then there should be an increase in water removal. Heating and the corresponding decrease in viscosity would occur where a majority of the water is being moved.

There was not always a direct correlation between density and SEM. For example, the unsteamed layered sheet showed a maximum SEM and conditioned density for the bottom layer, which is generally expected. The sheet steamed for 20 second showed a maximum SEM for the middle layer, while the minimum SEM was measured for bottom layer which had the maximum density. In contrast, steaming followed by the 200-second waiting time, produced a maximum SEM in the top layer which showed the minimum density.

The case of 20-second steaming tended to yield properties which were equal to or greater than those for the no steaming case. The 40-second steaming with 200-second waiting case tended to yield properties which were less than those for the case of no steaming. This result is intriguing because the total moisture gain and average temperature were the same for both cases. Both cases had approximately the same total energy content at pressing. The 200-second waiting case had a shallower moisture profile and an almost flat temperature profile as compared to the 20-second steaming case. This would seem to indicate that moisture profile as well as temperature plays a role in water removal and sheet property development.

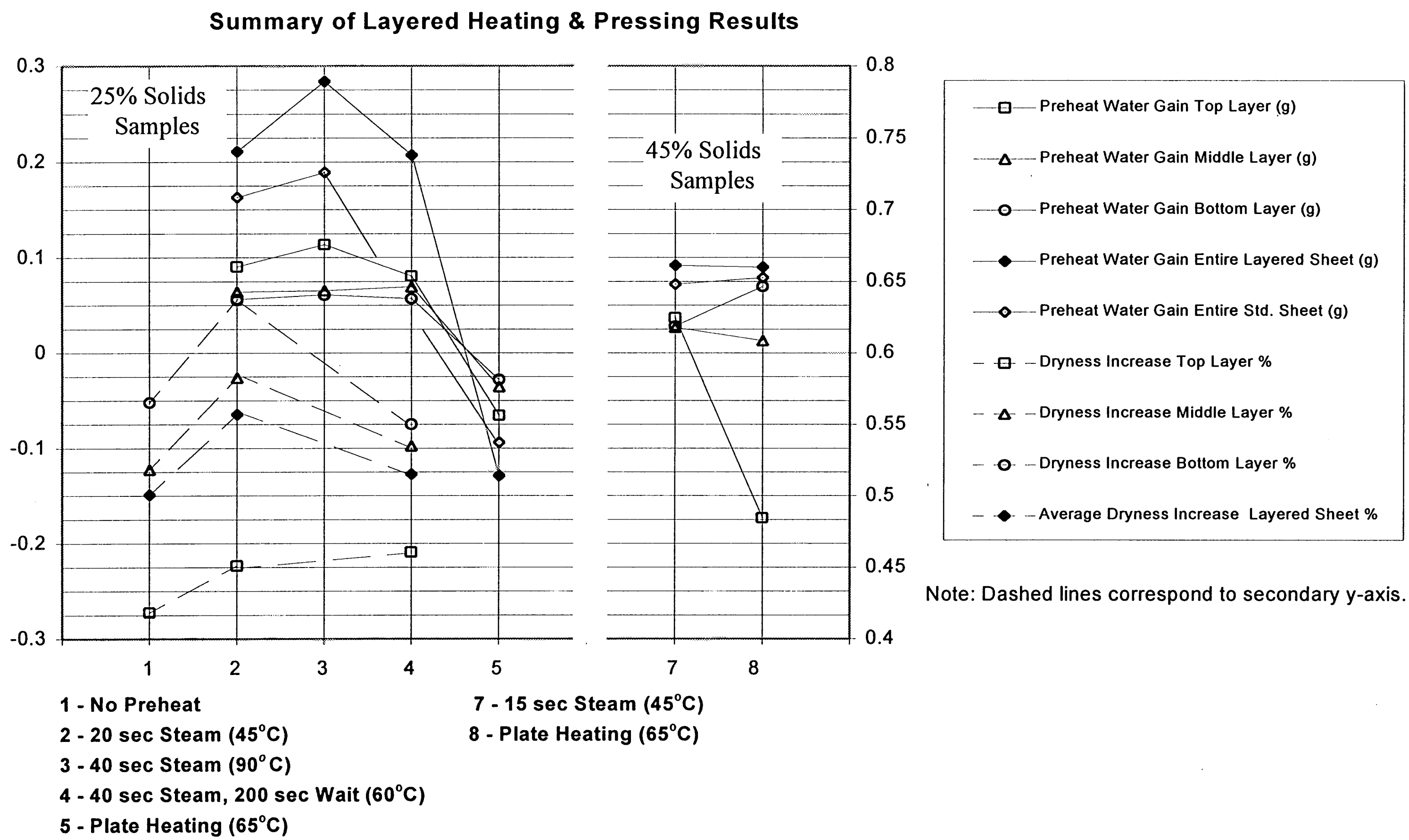


Figure 4.1 Water Gain During Heating and % Increase in Dryness

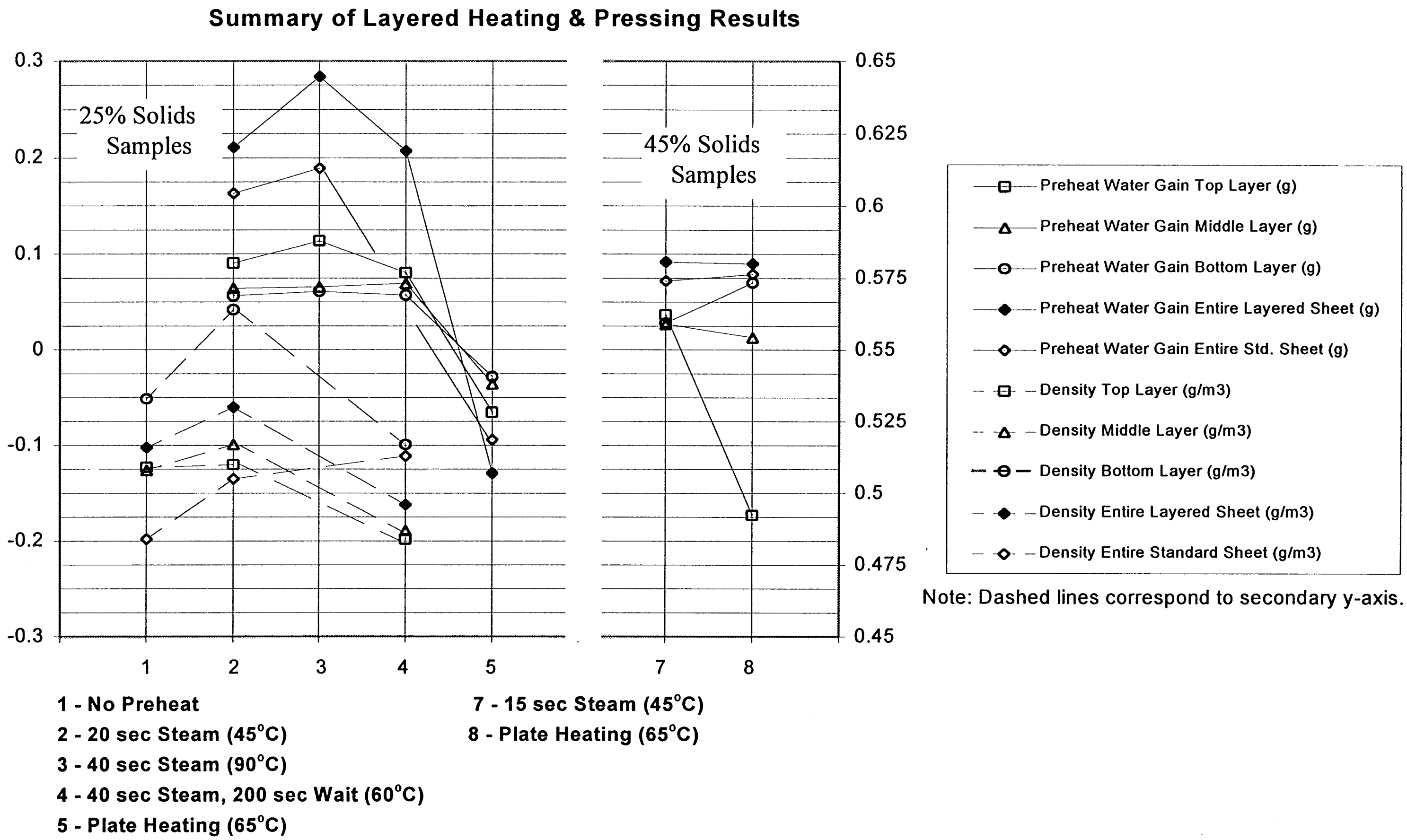


Figure 4.2 Water Gain During Heating and Conditioned Density

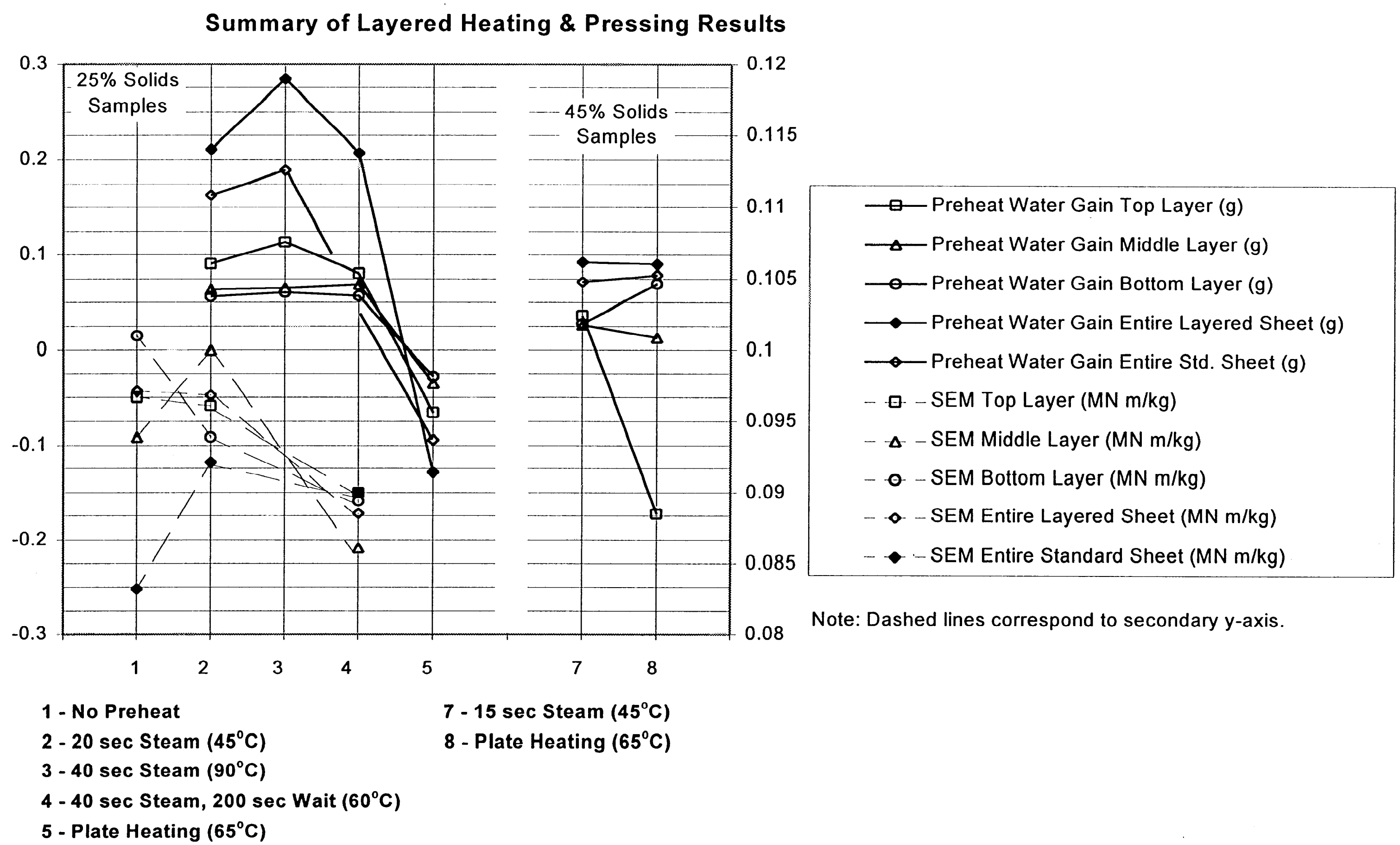


Figure 4.3 Water Gain During Heating and Conditioned Specific Elastic Modulus

4.5 Conclusions

The work with preheating and pressing of layered sheets yielded a number of conclusions:

1. Preheating alters the moisture profile of the sheet. Steam heating yields a moisture profile which has the greatest moisture at the top of the sheet and the least at the bottom of the sheet. Plate heating yields the opposite profile.

2. A waiting period after preheating reduces the temperature and moisture gradients in the sheet.

3. The bottom portion of the sheet shows the greatest water loss during pressing and the top portion shows the least water loss. Water removal is a nonuniform process with respect to vertical position within the sheet.

4. There is not always a direct correlation between sheet-conditioned density and sheet-conditioned specific elastic modulus.

5. Steaming to ~60°C and pressing immediately tended to yield greater water removal and more enhanced sheet properties than either steaming to 90°C and waiting 200 seconds until the average sheet temperature reached 60°C or no preheating at all. The result suggests that moisture profile as well as temperature profile play a roll in water removal and sheet property development.

5. Pressing of Nonlayered 205 gsm Sheets

5.1 Introduction

In these experiments water removal was characterized by the difference between outgoing and ingoing solids. Mechanical strength of the conditioned sheets was characterized by:

- specific elastic modulus (SEM);
- STFI Compression Index in cross machine direction (CD STFI).
- STFI Compression Index geometric mean of the machine direction (MD STFI) and cross machine direction (CD STFI).

Additionally, soft-platen conditioned density was measured as indicator of the sheet consolidation.

The single-stage pressing was performed first. Based on the results, a single steaming condition and a single plate heating condition were selected. The three-stage pressing, at ingoing solids of 25%, was then conducted using those preheating conditions as well as a no preheating condition. In the three-stage pressing, ingoing and outgoing weights were measured for all pressings. Based on the values of the hard-platen caliper prior to and after MTS wet pressing, apparent relative compression for each pressing was calculated as the difference of calipers divided by caliper prior to pressing.

5.2 Single-stage Pressing

The average water removal and mechanical strength properties produced by single-stage pressing at ingoing solids of 25% and 45% are plotted in Figure 5.1 andFigure 5.2.

The results from the whole-sheet, single-stage pressing showed a difference as compared to the results from the layered pressing. In the whole-sheet pressing the case of 40-second steaming with 200-seconds waiting prior to pressing yielded slightly greater water removal than the 20-second steaming case (for 25% solids). This was the opposite of what was found in the layered sheet pressing work. Thus, the layered structure apparently affected the water removal process to some extent. However, the whole sheet pressing data did support the conclusion that moisture profile has an effect on both water removal and sheet property development. The results also indicate the total moisture content is a factor, since similar preheating conditions produced different results for 25% and 45% solids sheets.

5.2.1 25% Solids Sheets

The layered preheating results showed that as steaming time increased, more moisture was condensed in the top surface of the sheet and a steeper moisture profile resulted. The top of the sheet was wetter than the bottom of the sheet. The results also showed, that as plate heating time increased the top of the sheet became drier, resulting in a moisture profile that was the opposite of that produced by steaming. The 25% solids results, particularly as shown by Figure 5.2, demonstrate that the sheets with the most water in the top portion of the sheet had the lowest water removal. Interestingly, the SEM results followed the same trend, but the density and CD STFI tended to follow the opposite trend.

Overall, the 15-second steaming, the 40-second steaming with 200-seconds waiting, and the two plate heating cases produced the highest water removal. The SEM results followed a similar trend. The density and CD STFI tended to follow a trend which increased with sheet temperature and then reached a plateau.

5.2.2 45% Solids Sheets

Figure 5.1 andFigure 5.2 show an additional 45% solids case. This is the 45% solids, no preheating using the same pressure pulse as was used for the 25% solids sheets. The results show that the dewatering is significantly less than that for the other 45% solids cases, i.e., the cases using the "standard 45% solids pressing pulse" which had a higher peak pressure and a greater impulse. This demonstrates the generally accepted concept that increasing peak pressure and impulse increases dewatering.

At ingoing solids of 45%, the benefits of steaming were less pronounced than with the 25% solids sheets. This is again consistent with the results obtained in previous experiments (Appendix B, Table 6).

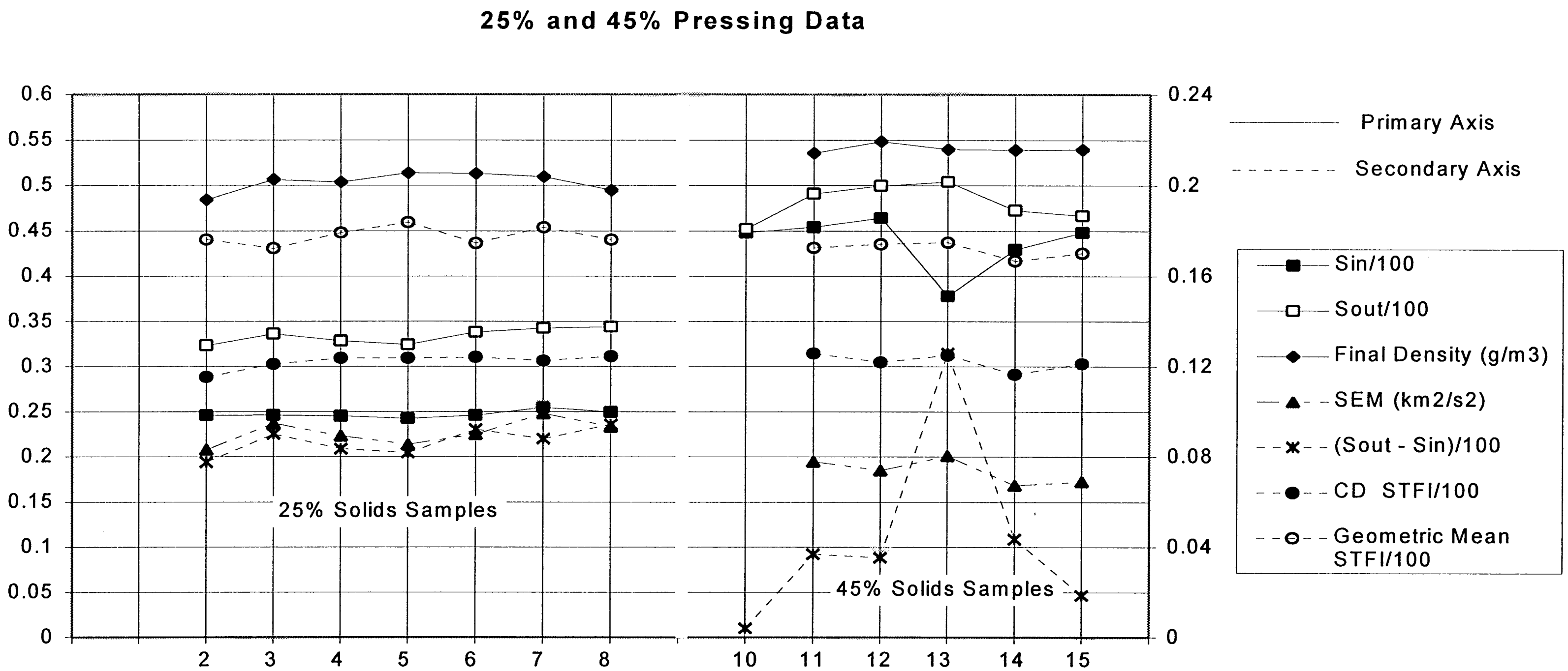
In the 45% solids results the case of 40-second steaming is somewhat exaggerated because the ingoing moisture was approximately 38% instead of the desired 45%. As with the 25% solids cases, SEM and water removal followed similar trends. Unlike the 25% solids cases, density and CD STFI did not follow a similar trend. This may be attributed to the limited changes in density. The increases as the moisture content of the top of the sheet increases. Also, the plate heating yielded results which were in general less than those for the no preheating case. Plate heating resulted in considerable drying out fibers in the top part of the sheet. It is believed this caused decreased bonding between fibers which resulted in a noticeable decrease of SEM and STFI data. There is the possibility that increasing the peak pressure pulse may result in an increase in some of these properties, however, as the fibers dry out there is a point at which increasing peak pressure has no effect on bonding.

5.2.3 Conclusions

The results support the concept that moisture profile as well as total moisture content affect both water removal and sheet property development. The relationship changes as sheet solids is increased.

In the case of 25% solids, increasing the moisture content of the top of the sheet beyond a certain level tends to decrease the water removal and SEM. Density and CD STFI tend to increase with sheet temperature, regardless of moisture profile, and then level off. Only a significant decrease in the moisture content of the top of the sheet can cause a decrease in SEM or density. Heating, depending on the moisture profile produced, can have a positive impact on sheet properties.

In the case of 45% solids, dewatering increases with increasing moisture at the top surface of the sheet. Any decrease in the moisture at the top surface results in decreased water removal, SEM, and CD STFI. Heating in general does not have a significant positive impact on sheet properties.



2 - No Preheat
3 - 15 sec Steam (45°C)
4 - 25 sec Steam (60°C)
5 - 40 sec Steam (90°C)
6 - 40 sec Steam, 200 sec Wait (60°C)
7 - Plate Heating (58°C)
8 - Plate Heating (77°C)

10 - No Preheat, same peak pressure as 25% solids
11 - No Preheat, Standard 45% peak pressure
12 - 15 sec Steam (45°C), Standard 45% peak pressure
13 - 40 sec Steam (90°C), Standard 45% peak pressure
14 - Plate Heating (58°C), Standard 45% peak pressure
15 - Plate Heating (77°C), Standard 45% peak pressure

Figure 5.1 25% and 45% Solids Pressing Data

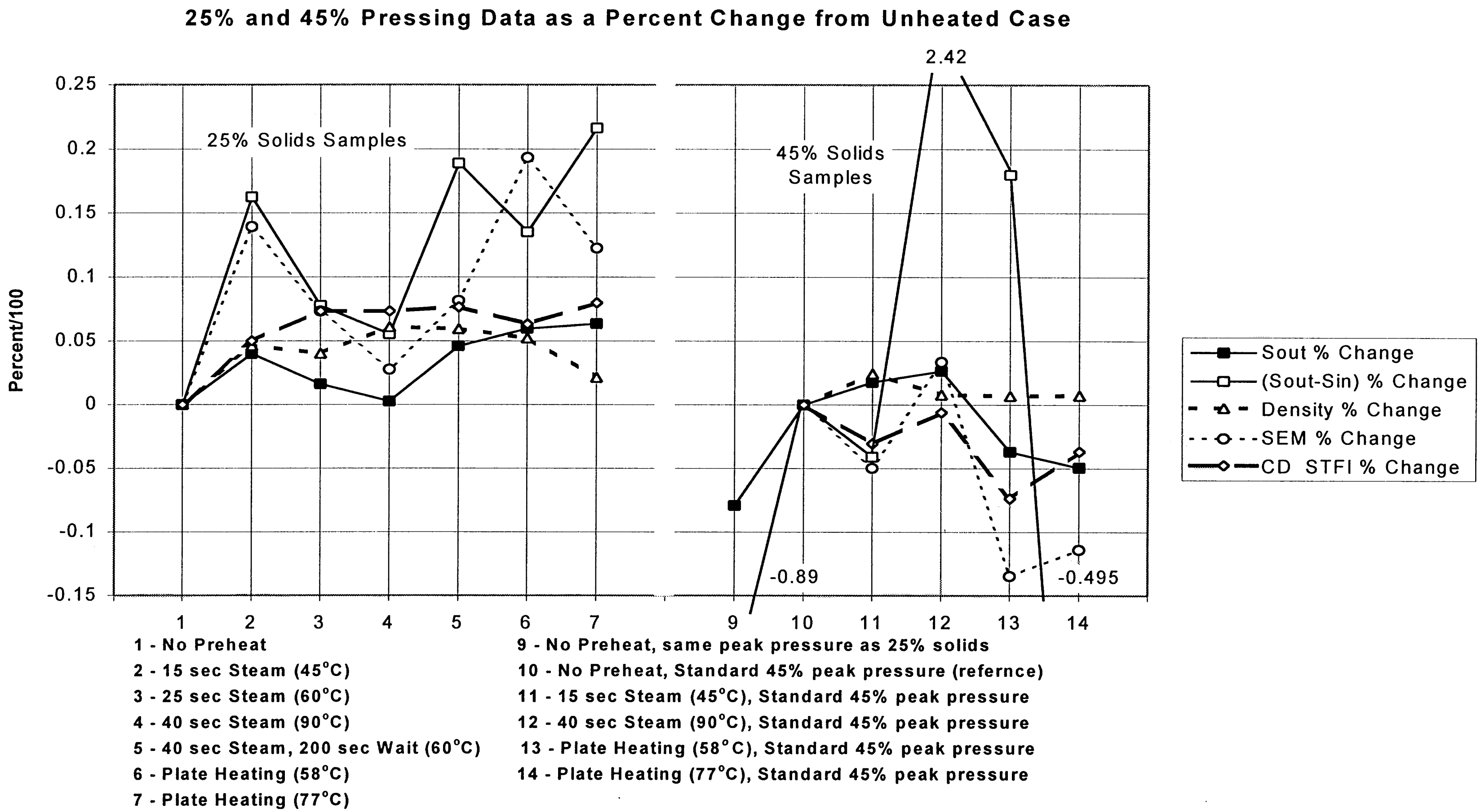


Figure 5.2 25% and 45% Solids Pressing Data as a Percent Change.

5.3 Three-stage Pressing

Three-stage pressing was performed to determine potential of sheet preheating. It is an idealization of a three press configuration with preheating before each press. In this experiment ingoing solids were 25% prior to the first pressing and preheating was identical prior to each pressing.

Steaming was conducted for 15 seconds resulting in an average sheet temperature of 45-50°C. Plate heating was carried out for 20 second at a plate temperature 65°C resulting in an average sheet temperature of ~58°C. Data on water removal and mechanical strength are plotted in Figure 5.3 throughFigure 5.5.

The benefits of preheating are obvious both in terms of water removal and mechanical strength when compared with the case of no heating. Steaming is especially productive. The resultant increase in strength is on order of 12-14%. Apparent compression increased with heating, which is assumed to have been caused by higher conformability of fibers and lower spring back at elevated sheet temperature. The advantages of plate heating are also significant but slightly lower than that of steam.

The selection of pressure pulses which were optimum for the ingoing solids contents was attempted. It was expected that as the solids increased, the total change in properties produced by each succeeding pressing would also decrease. However, the results consistently show the second pressing yielded a lesser change in properties than either the first or third pressing. This suggests that the pressure pulse used for the second pressing was not adequate; the peak pressure and impulse should have been higher.

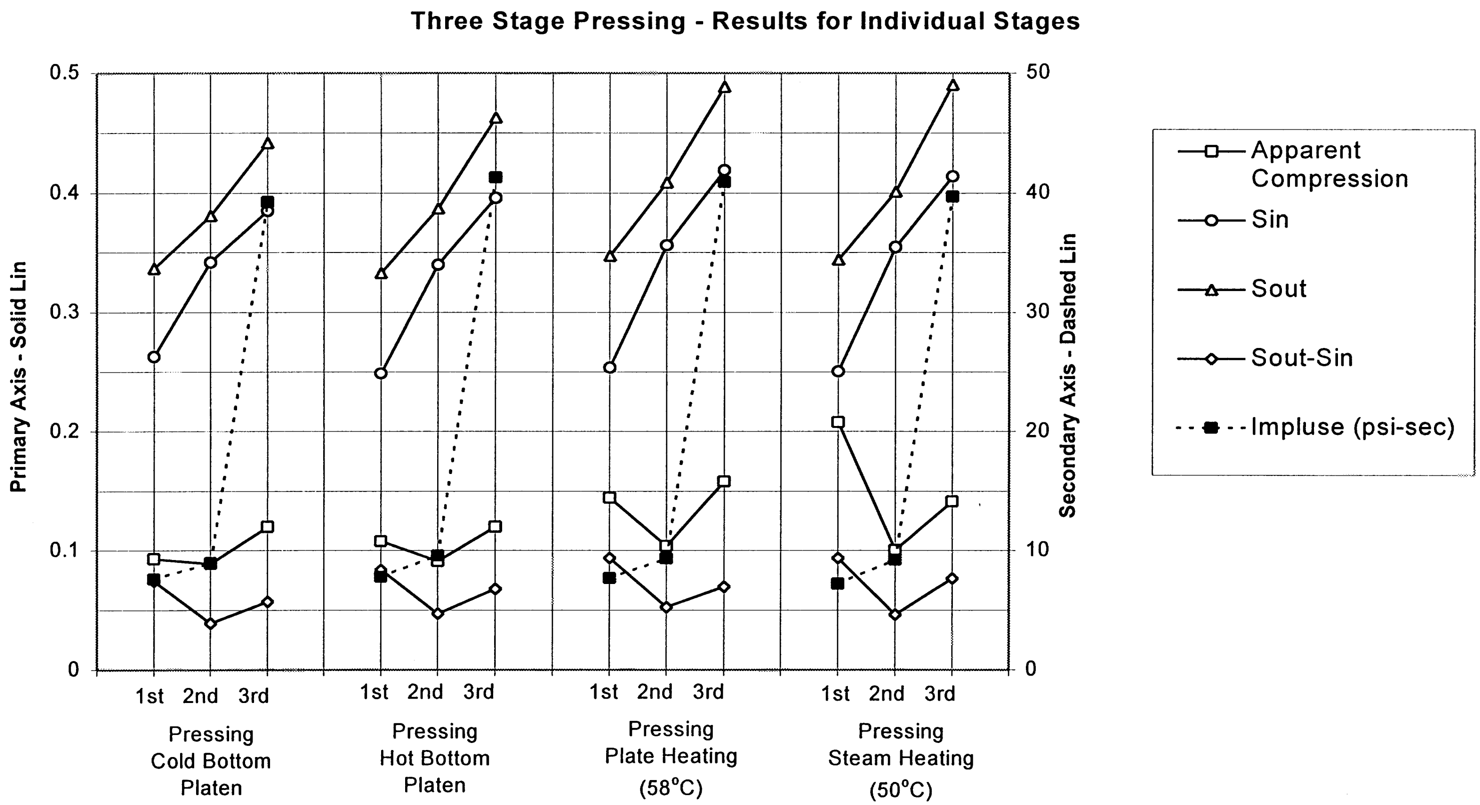


Figure 5.3 Three-stage Pressing - Results from Individual Stages

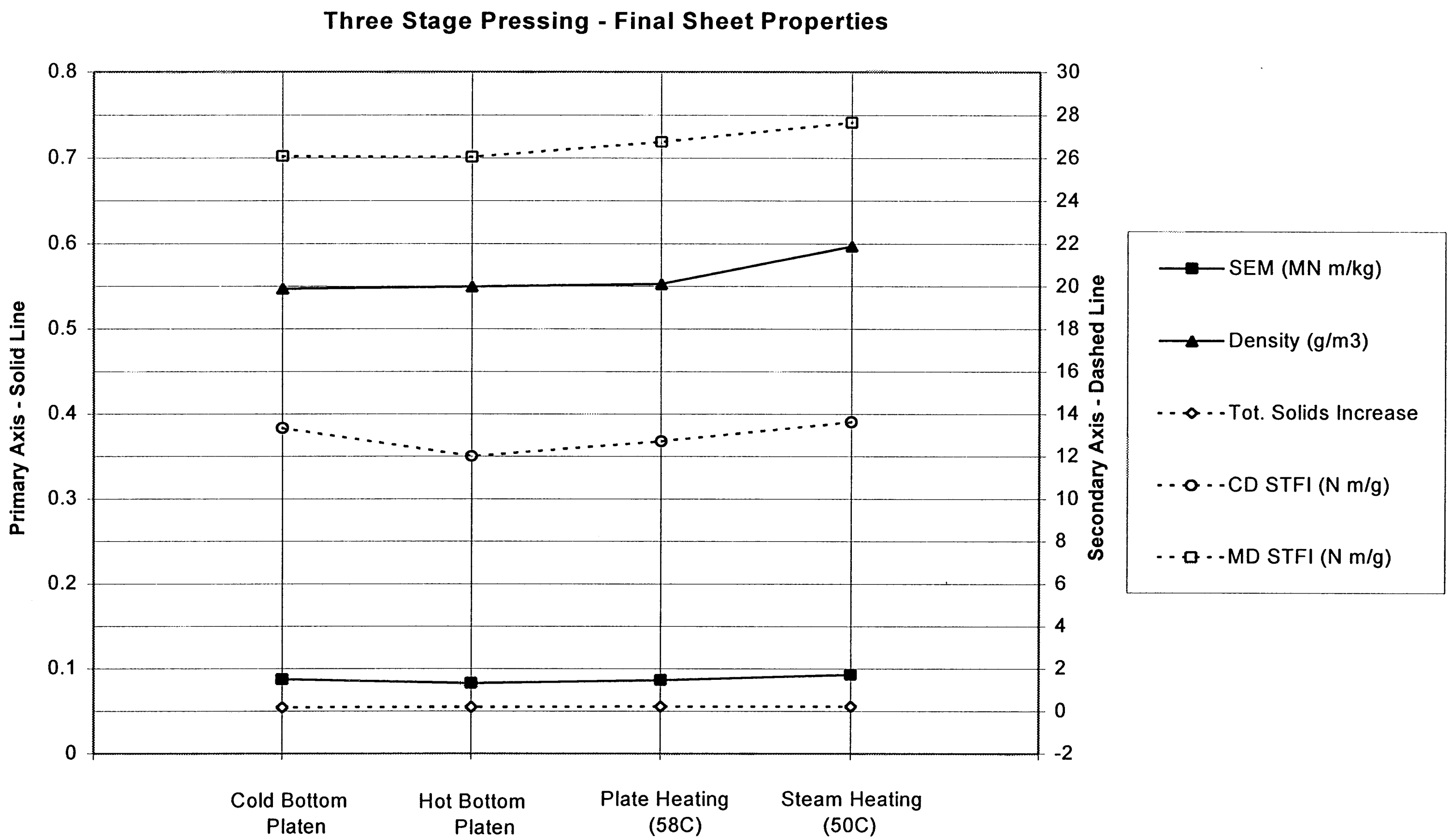


Figure 5.4 Three-stage Pressing - Final Sheet Results

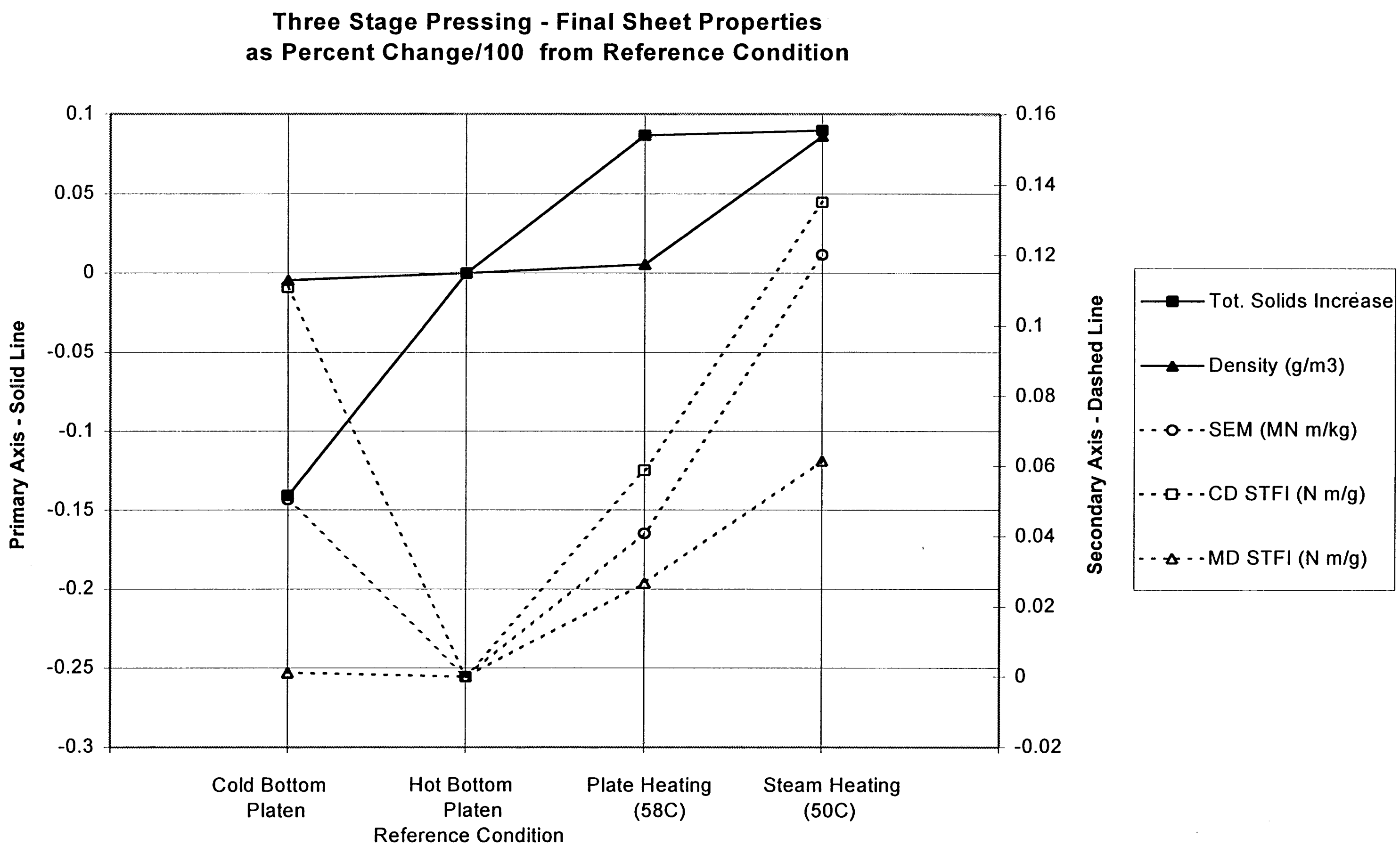


Figure 5.5 Three-stage Pressing - Final Sheet Results as a Percent of Reference Condition

6. Conclusions

The effect of ingoing sheet solids and temperature on water removal and mechanical strength of paper using different preheating methods was addressed in this work. Single pressings were performed on layered and whole sheets using various preheating methods. Three-stage pressing was conducted using selected preheating methods to determine the potential of preheating in a three press configuration. The results make possible the following conclusions:

1. The beneficial effect of the sheet preheating is determined not only by increased sheet temperature but also by the changes in the solids profile during preheating. Accumulation of excessive moisture in the top part of a steamed sheet may cause a decrease in water removal in spite of an increase of sheet temperature. Alternatively, excessive moisture evaporation in the top part of a plate-preheated sheet may cause drying out of fibers, a deterioration of the sheet consolidation, and a drop in mechanical strength.

2. At an ingoing solids of 25%, moderate preheating by steam and hot plate resulted in an increase of water removal and mechanical strength. Strength characteristics were also high. Steam preheating could result in a decrease in dryness due to accumulation of condensate in the top part of the sheet.

3. At ingoing solids of 45%, preheating by steam had less pronounced benefits than that at 25%. The same was true of plate heating. Plate heating also caused considerable drying of the top surface with a resultant detrimental effect on strength properties.

4. Three-stage preheating showed that steaming produces significantly improved water removal and strength of the sheet as compared with the no preheating case. Advantages of plate preheating were less pronounced, but were also significant.

5. Comparing the results from 25% and 45% single-stage pressing, from the three-stage pressing, and from Appendix B, there appears to be a threshold pressure pulse (peak pressure and/or impulse) required to obtain maximum benefit from preheating in a particular pressing application. If the pressing pulse is inadequate, little or no benefit will be obtained from preheating in terms of water removal. Sheet strength increases will also be affected.

It appears that the ideal preheating method is one which leads to a maximum increase of sheet temperature and a slight increase in solids in the top part of the sheet at low ingoing solids and does not change solids profile at high ingoing solids.

References

1 Patterson, T.F., Iwamasa, J.M. First Steambox Comparator Experiment: Initial Investigation of Steambox Performance. Project F002. Progress Report to the Member Companies of IPST - Report 2. (August 1997)

Appendix A 2nd MTS Pressing Detailed Data

25% SOLIDS	20 SEC STEAM		40 SEC STEAM		40 SEC/200 SEC waiting STEAM		65°C / 25 SEC HOT PLATE	
	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
Top	0.429	0.0905	0.400	0.114	0.389	0.0805	-0.508	-0.0655
Middle	0.304	0.0641	0.311	0.088	0.335	0.0693	-0.275	-0.0355
Bottom	0.267	0.0563	0.289	0.082	0.276	0.0571	-0.217	-0.028
Total Water Gain for Layered Sheet, g	0.211		0.284		0.207		-0.129	
Total Water Gain for Whole Sheet, g	0.163		0.189		0.089		-0.094	
45% SOLIDS	15 SEC STEAM		40 SEC STEAM				65°C / 25 SEC HOT PLATE	
Top	0.401	0.0369	0.420	0.0445			-1.922	-0.173
Middle	0.291	0.0268					0.144	0.013/
Bottom	0.308	0.0283					0.778	0.070
Total Water Gain for Layered Sheet, g	0.092		0.106				0.090	
Total Water Gain for Whole Sheet, g	0.072		0.0636				0.079	

Table 7.1 Layered Sheet Water Gain/Loss During Preheating

	No Steam			20 Second Steam			40 Second Steam/ 200 Second Wait		
	% Increase Dryness	Solids Out %	Mass Water Lost (g)	% Increase Dryness	Solids Out %	Mass Water Lost (g)	% Increase Dryness	Solids Out %	Mass Water Lost (g)
Top Layer	4.184	0.260	0.159	4.512	0.261	0.171	4.606	0.262	0.175
Middle Layer	5.185	0.263	0.196	5.827	0.265	0.218	5.349	0.263	0.201
Bottom Layer	5.654	0.264	0.212	6.371	0.266	0.238	5.502	0.264	0.207
Average	5.008			5.57			5.152		
Whole Sheet		0.263	0.567		0.264	0.627		0.263	0.583
Ratio of increase in dryness: top	1			1			1		
middle	1.239			1.291			1.161		
bottom	1.351			1.412			1.195		

Figure 7.6 Layered Sheet Water Removal from Pressing

		No steam	Steaming 20 sec	Steaming 40sec/200sec waiting
		Specific Elastic Modulus, MN m/kg		
Top Layer	Average	**0.0967**	**0.0961**	**0.090**
	StdDev	0.00950	0.00813	0.00566
Middle Layer	Average	**0.0939**	**0.100**	**0.0861**
	StdDev	0.0110	0.0127	0.00446
Bottom Layer	Average	**0.101**	**0.0939**	**0.0894**
	StdDev	0.0103	0.0127	0.00495
	Layered Sheet Average	**0.0971**	**0.0968**	**0.0885**
	Whole Sheet Average	***0.0832***	***0.921***	***0.090***

		No steam	Steaming 20 sec	Steaming 40sec/200sec waiting
		Conditioned Density, g/cc		
Top Layer	Average	**0.509**	**0.510**	**0.484**
	StdDev	0.0209	0.0349	0.0255
Middle Layer	Average	**0.508**	**0.517**	**0.487**
	StdDev	0.0257	0.0368	0.0239
Bottom Layer	Average	**0.533**	**0.564**	**0.517**
	StdDev	0.0269	0.0368	0.0266
	Layered Sheet Average	**0.516**	**0.530**	**0.496**
	Whole Sheet Average	***0.484***	***0.505***	***0.513***

Table 7.2 Layered Sheet - Specific Elastic Modulus and Conditioned Density

Appendix B - Pressing of Heated Sheets
First MTS Experiments

1. SUMMARY

This work is part of a project that has two areas of concentration:

1. Web Preheating.
2. Pressing of Heated Webs.

The work documented here is the first effort at addressing item 2. Previous researchers have investigated the effect of sheet preheating on pressing results. The work of these researchers is reviewed in [1]. While the earlier work is valuable, it does not focus significant attention on the heating method used to preheat the sheet or the sheet moisture profile produced by the heating. The results of the work presented here, indicate that moisture profile can be significant. The work utilized a single pressure pulse, OCC linerboard sheets at a single basis weight, 205 g/m^2, three solids levels 25%, 35%, and 45%, steaming as a means of increasing the sheet temperature, and various ingoing sheet temperatures. Sheet apparent density, compression, air permeability, specific elastic modulus, and STFI compression strength were measured.

The results of the research indicate that at the lowest ingoing solids level, an increase in ingoing temperature leads to an increase in water removal. Increasing ingoing solids reduces the positive effect of elevated ingoing temperature on water removal. In general, similar trends were observed in the behavior of mechanical strength as characterized by specific elastic modulus and STFI compression strength. Of the various steaming protocols used to heat the sheets, those that apparently produced the most even moisture profile produced the greatest increase in properties for a given solid level.

The rise in ingoing sheet temperature, resulted in a significant increase of apparent compression of the pressed sheet for each ingoing solids. Low ingoing solids and high ingoing temperature resulted in highest compression of the sheet. There was limited change for the high ingoing solids sheets, this may have been due to an inadequate pressing impulse.

MTS pressing resulted in a noticeable increase in air permeability of the sheets that were not steamed. Steaming led to a reduction of air permeability for lower ingoing solids. At high ingoing solids, air permeability after MTS pressing was higher than prior to pressing, but less than for pressing without preheating.

2. EXPERIMENTAL PROCEDURES

2.1 Introduction

Water removal from paper and consolidation of the web are more intensive at elevated temperatures due to decreased hydraulic resistance (viscosity), decreased surface tension, and increased fiber compressibility. Therefore, improvements in pressing efficiency can be achieved by increasing the temperature of the sheet prior to pressing.

The objective of the present work was to explore the effect of ingoing sheet temperature and ingoing solids on mechanical strength and water removal by simulating the sheet pressing process using an electrohydraulic platen press (MTS Press). Throughout the testing the pressing parameters and the platen temperature were held constant

2.2 Sample Fabrication and Prepressing

The 42# (205 gsm) handsheets used in this project were made on a Formette Dynamique Sheet Former from 616 ml CSF OCC pulp. The sheets were formed and dewatered at a speed of 1800 m/min. After light prepressing on a Baldwin Press (one dimensional vertical press) to a solids level of 25%, two thirds of all the sheets were prepressed on a slow speed laboratory roll-press to 35%. One half of the 35% solids sheets were then pressed on the same roll press to 45% solids. Thus, there were equal numbers of sheets at each solids level. Each Formette sheet measured 88.9 cm x 21.6 cm (35 in x 8.5 in) and was die cut to provide samples for pressing and water permeability tests. The pressing samples were cut into 7.62 cm x 6.35 cm (3 in x 2.5 in) rectangles. The samples were cut with the Formette MD and CD directions parallel to the sides of the rectangular samples. Samples for the water permeability test were cut using a 7.62 cm (3 in) diameter circular die.

2.3 MTS Wet Pressing

The pressing work was performed using a laboratory-scale electrohydraulic platen press (MTS press). The platen surface contacting the sheet had a ceramic coating, which limited, to some extent, sticking of the sheet to the surface. Pressing was carried out at a constant platen temperature of 65°C.

Since pressing was to be conducted at three solids levels and only a single pressing pulse was to be used, an intermediate peak pressure was chosen. A typical pressure curve is shown in Figure 1. The duration of pressure pulse was about 20 msec, maximum pressure varied in the range of 6100- 6600 KPa (880-940 psi). The pressing impulse was in the range of 48.9-51.0 KPa sec (7.0-7.3 psi sec). This pressing pulse was a compromise between what would be used for a low solids sheet and what would be used for a high solids sheet. It was lower than those used in [3,4] which was equivalent to that produced by a shoe press. In [3,4] the ingoing solids were 35%, the pressure impulse was 213 KPa sec (30.5 psi sec), and the average nip pressure varied from 3500 KPa (500 psi), using a soft nip, to 8400 KPa (1200 psi), using a hard nip.

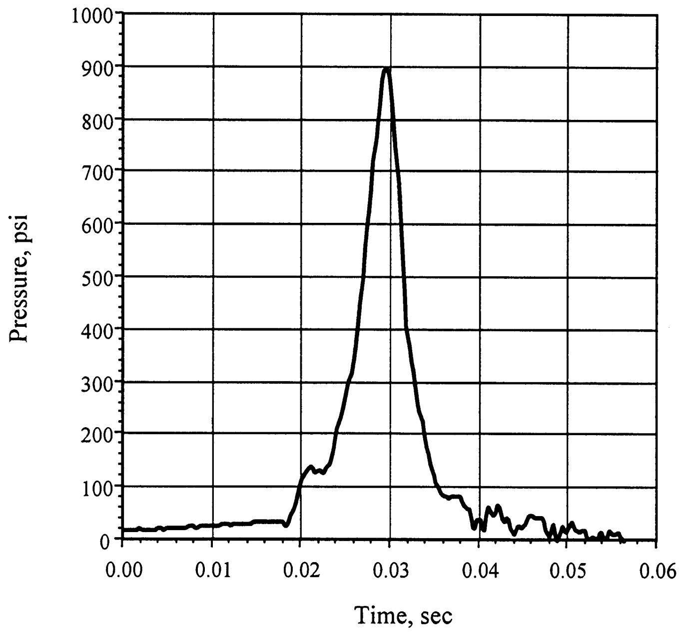


Figure 1. Typical Pressure Pulse

2.4 Experimental Conditions and Testing

In this study it was attempted to quantify, to the greatest extent possible, the condition of the sheets both prior to and after pressing. The sheet conditions prior to pressing were:

- Ingoing solids - 25%, 35%, and 45%
- Ingoing temperature - ambient, 60 °C, and 90 °C

The following measurements were made prior to pressing:

- water permeability on hydraulic Carver Press
- hard-platen caliper
- air permeability on Gurley Porosimeter

After the sheets were wet pressed on the MTS press, the sheets were split into two groups. One group was subjected to hard-platen caliper and air permeability measurements while still moist. Based on the values of hard-platen caliper prior to and after MTS wet pressing, apparent relative compression was calculated as the difference of calipers divided by caliper prior to pressing. The sheets in the other group were dried under constraint using a heated platen at low pressure, then preconditioned (20%

humidity, 21°C (72°F)) and conditioned (50% humidity, 21°C (72°F)) The conditioned sheet were then used for the following tests:

- soft-platen density
- out-of-plane (z-direction) ultrasound to determine specific elastic modulus
- STFI short span compressive strength test in the MD and CD directions (TAPPI Standard Test T 826 om-92)

2.5 Temperature Calibration

Since the ingoing temperature of the wet pressed sheet was a variable, experiments were conducted to identify the heating time required to preheat the sheet to various ingoing temperatures. To this end, sheets with embedded thermocouples were prepressed to solids contents of 25% and 45% and used for a steaming temperature calibration. The sheets were five-ply. Each layer was 41 g/m^2 for a combined basis weight of 205 g/m^2. Thus, each sheet could have employed six thermocouples, four embedded in the sheet, one on the top, and one on the bottom. Since the data acquisition system could record data from only four thermocouples, the thermocouples were positioned as follows:

1st thermocouple,	T_1,	$z = 0.0\,L$
2nd thermocouple,	T_2,	$z = 0.4\,L$
3rd thermocouple,	T_3,	$z = 0.6\,L$
4th thermocouple,	T_4,	$z = 1.0\,L$,

where L is the thickness of the sheet and $z = 0$ is the interface between the sheet and the felt. The average temperature of the sheet, T_{av}, was calculated as a weighted mean:

$$T_{av} = 0.2\,(T_1 + T_2) + 0.1\,(T_2 + T_3) + 0.2\,(T_3 + T_4).$$

It is important to note that the steam heating of the sheet did not occur in the same manner as it would with a steambox. In a steambox, the steam is directed generally perpendicular to the sheet, the pressure in the steambox is on the order of 69-105 KPa (10-15 psi). In this experiment, the sheet was steamed using low speed steam emitted from an enclosure containing the steam at 14-21 KPa (2-3 psi). The steam was directed at the top of the sheet but the flow was not perpendicular to the surface. The temperature of the steam near the surface of the sheet was about 100°C. It was expected that the prevailing mechanism of heat transfer would be through steam condensation while convection would be minimal. Since the felts were not ideally flat, part of the steam penetrated into the space between sheet and felt.

In the steaming tests, the sheets were placed on the top of a felt (16% moisture content) and were steamed for 40 sec, then the steam was shut off and the sheet was allowed to cool off for 200 seconds. The temperature profile was recorded and average temperatures were calculated. The results are summarized in Table 1. As can be seen from the table, a sheet temperature of 60°C could be attained by one of two means, either steaming for short time or steaming for 40 seconds followed by a cooling off period of 200 seconds.

Solids, %	Average Sheet Temperature		
	60 °C	60 °C	90 °C
25	14.4s +/-1.7s	40s / 200s cooling	40s
35	16.0s +/- 1.4s	40s / 200s cooling	40s
45	17.4s +/- 3.6s	40s / 200s cooling	40s

Table 1. Steaming Time Required to Attain Ingoing Temperature

Each sheet with embedded thermocouples was steamed 6 times. Before each subsequent steaming, the sheet was allowed to cool off and then was conditioned to the target ingoing solids.

2.6 Steaming Weight Calibration

Since steaming adds weight to the sheet through condensation a calibration of that weight gain was required. This allows the ingoing weight of the samples to be adjusted so that when each is pressed, it is at the desired solids content. The steam weight gain calibration was carried out at ingoing solids of 25%, 35%, and 45% by steaming the sheet for 40 seconds steaming to attain 90°C and by steaming for 40 seconds followed by 200 seconds of cooling to attain 60°C. Five samples were used for each condition. The average gain in the sheet weight was determined and is plotted in Figure 2.

The greater weight gain for the lower solids sheets was due to the greater water content and therefore greater heat capacity, C_p and thermal conductivity, k. Assuming that for water k = 0.63 W/m °C and for fiber k = 0.049 W/m °C, and using a mass weighted average the thermal conductivity is 0.485 W/m °C at 25% solids and 0.369 W/m °C at 45% solids. The greater condensation rate for the lower solids sheets does not result in higher average temperatures because the wetter sheet has a higher volume heat capacity than the drier one. Assuming for water C_p = 4.19 J/cm^3 °C and for fiber C_p = 2.06 J/cm^3 °C, the volume heat capacity is 3.66 J/cm^3 °C at 25% solids and is 3.23 J/cm^3 °C at 45% solids.

The results of steam calibration were used to insure the ingoing weights of the sheets were at the target values just prior to MTS pressing. Assuming that the basis weights of all the sheets were 205 g/m^2 (42lb/1000ft^2), the oven-dry weight of the 7.62 cm x 6.45 cm (3 in x 2.5 in) sheet was 0.992 g. The target values of ingoing weights for different ingoing solids and temperatures are tabulated in Table 2. If the weight gain was not accounted for an error in the value of the ingoing solids of up to 2% could have resulted.

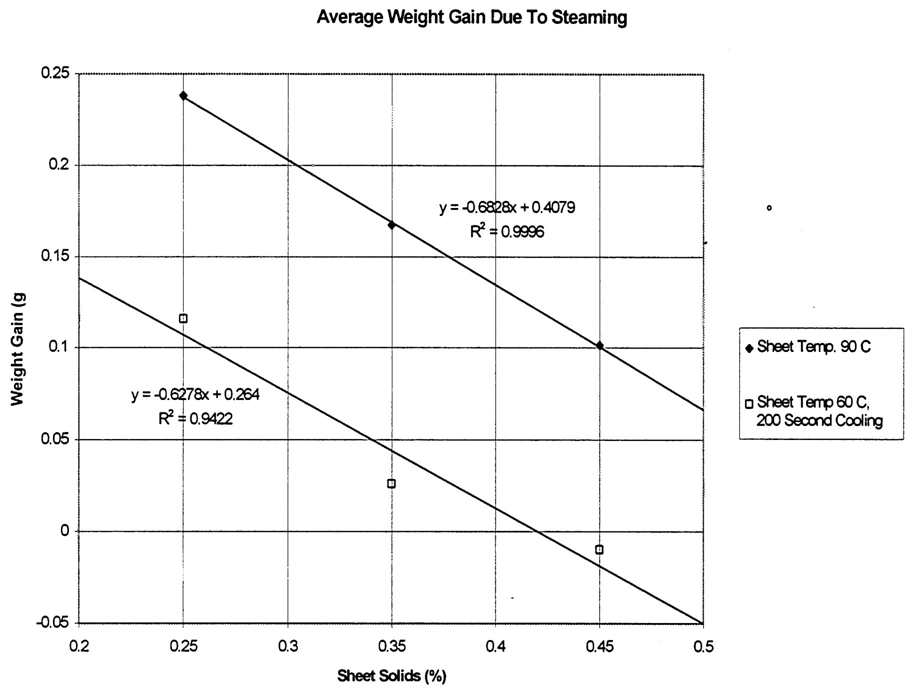


Figure 2. Sheet Weight Gain Due to Steam Heating

Ingoing Solids, %	90 °C	60 °C	Room Temperature
25	3.730 g	3.852 g	3.968 g
35	2.667 g	2.808 g	2.834 g
45	2.103 g	2.214 g	2.204 g

Table 2. Target Ingoing Sheet Weights

2.7 Water Permeability Measurements

Water permeability measurements were carried out on the Carver Press. Prior to testing, the sheets were submerged in water and deaerated for two hours at a vacuum level of 381 mm Hg (15 in Hg). The sheets were kept submerged in the water for 15-20 minutes before testing. The sheets prepressed to 25% were not kept submerged as these sheets began to fall apart. Measurements were conducted at compressive loads in the range of 890-2900 N (200-650 lbs). The pressure differential across the sheet was adjusted to ensure a flow rate of not less than 1 g/min.

Since water permeability rapidly decreases with the sheet compression, it is frequently characterized by specific surface area of the fibers exposed to the flow. Specific surface area may be calculated from the dependence of water permeability on sheet caliper. In general, when permeability increases, specific surface drops. The results are plotted in Figure 3.

The results show that as solids increased specific surface dropped, which was expected. The variability of the specific surface at solids levels of 35% and 45% was relatively high, 31.6 and 29.2%, respectively. The lowest variability 17.7% was observed at a solids level of 25%. The higher variability could have been the result of partial removal of sheet fines during the dearation process. It should be kept in mind that the measurement of water permeability has some inherent variability.

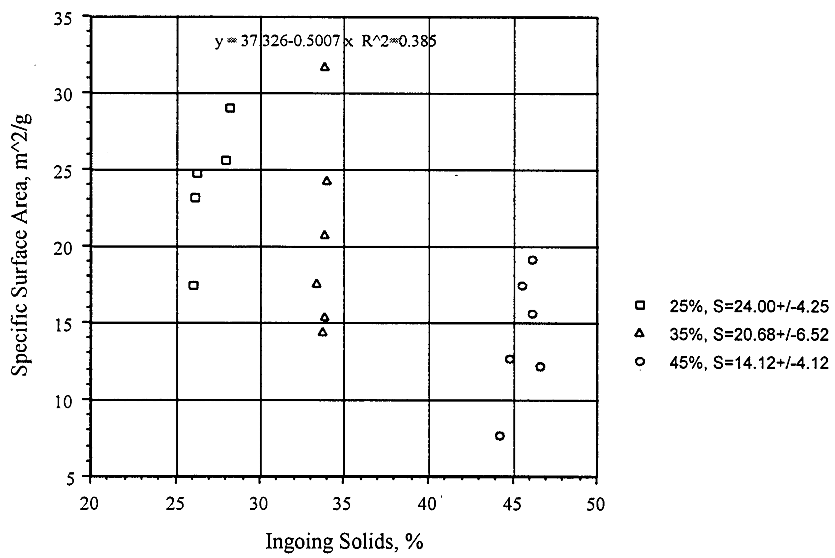


Figure 3. Specific Surface Area from Water Permeability Test vs Ingoing Solids

2.8 Air Permeability Measurement

Air permeability measurements were performed on the wet samples prior to and after MTS pressing using a Gurley Porosimeter. The measurement can take from a few seconds to tens of minutes.

The value of z-direction air permeability can be defined using Darcy's Law in the form of,

$$K = \mu Q L / (A \Delta p)$$

where Q is air flow rate, L is the caliper, A is the test area, and Δp is the pressure differential through the thickness of the sheet. All are measured quantities. The quantity μ is the dynamic viscosity of air. The values of Q, Δp, A, and L are measured quantities. Once measured, the permeability, K, can be readily calculated.

The Gurley Porosity tester used for this testing produced a pressure differential of Δp = 1.22 kPa. The flow area was A = 6.4 cm^2, and the air dynamic viscosity was μ =1.821 x 10^{-5} kg/(m °C s) at 20°C.

The volume air flow rate, Q, is inversely proportional to the Gurley Porosimeter reading

$$Q = 100/g$$

where g was the Gurley Porosimeter reading in sec/100cm^3.

The caliper of the sheet was measured by an electronic gauge from AB Lorentzen & Wettre with an accuracy of 1 micron. To avoid damage to the sample and decrease drift in the measurement, the wet sheet was placed between two thin plastic plates of known caliper during the caliper test.

Substituting the measured values into Darcy's equation and simplifying yields the following:

$$K = 2.332\ 10^{-12}\ L[\text{mm}]/(g[\text{sec}/100\ \text{cm}^3]),\ \text{m}^2.$$

3. RESULTS AND DISCUSSION

3.1 Water Removal

In commercial applications, water removal is frequently characterized by the difference between ingoing and outgoing solids or increase in solids (dryness). The average values of increase in solids for all cases are plotted in Figure 4.

The graph shows that steaming resulted in a noticeable increase in outgoing solids at a ingoing of solids 25%. The increase in solids at a sheet temperature of 60°C was higher than at 90°C which is inconsistent with the generally accepted concept that dewatering always increases with sheet temperature. The increase in the sheet temperature from ambient to 60°C resulted in a dryness improvement of 9.54 - 6.26 = 3.28%. This results in 1.1%/10 °C which is slightly higher than the often quoted "rule of thumb" for characterizing the efficiency of steaming, i.e., 1%/10 °C [2]. The increase in the sheet temperature from ambient temperature to 90°C led to dryness improvement of 7.46-6.26 = 1.2%, or 0.2%/10°C.

The most probable explanation for the difference in water removal is that the steaming process used to reach 60°C and the process used to reach 90°C produced sheet moisture profiles which were significantly different. The steaming process used to reach temperature 60°C, included 40 seconds of steaming (identical to the process used to reach 90°C) and a cooling off period of 200 seconds. This cooling off period provided time for the condensed steam, which was initially concentrated at the top of the sheet, to both evaporate off the top and diffuse into the rest of the sheet. Referring to Figure 2, and comparing the sheet water gain for the two steaming processes, it can be seen that in the 60°C case more than half of the condensed steam evaporated during the waiting time. In the 90°C case pressing was initiated immediately after steaming, thus there was little time for evaporation to occur.

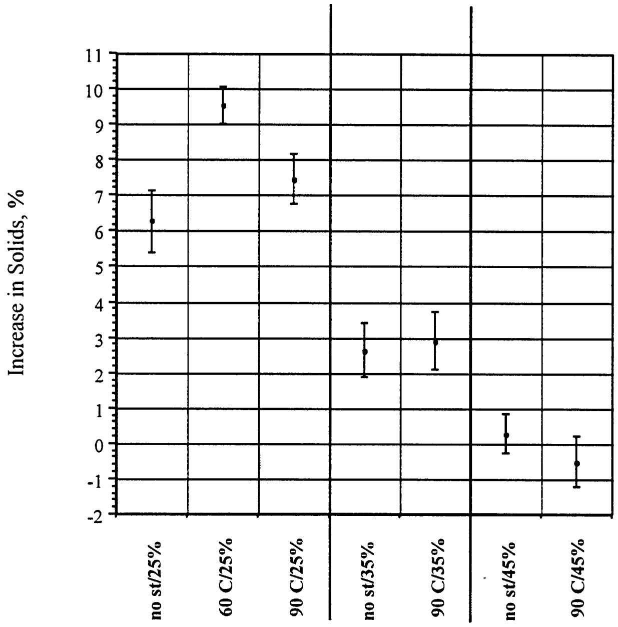


Figure 4. Average Increase in Solids

The literature provides some support for the idea of moisture profile influencing water removal. Previous researchers have proposed a qualitative description of sheet structural and hydraulic pressure distributions with respect to sheet z-direction position and nip time [3, 4]. This description states that the hydraulic component of pressure is highest on the top (press) side of the sheet and that it decreases with movement towards the bottom of the sheet. Assuming that dewatering is proportional to the hydraulic component of total pressure [2], it can be hypothesized that the solids profile which has a minimum solids level at the top of the sheet and a maximum solids level at the bottom of the sheet (the 90°C case) is not optimum for efficient water removal. This is because water is removed from the bottom of the sheet and in this case more of the water is at the top of the sheet. High water removal requires that some water pass through the entire sheet, a process which requires that the hydraulic pressure gradient not drop off too rapidly. In the case of a more even moisture profile, a greater percentage of water is at the bottom of the sheet, a position from which it is easily removed from the sheet.

Figure 4 also showed that as the ingoing solids increased, the efficiency of steaming in terms of water removal decreased. At an ingoing solids 35%, the increase in water removal was marginal. The improvement in dryness was only 0.69%. At an ingoing solids 45%, steaming resulted in a minor decrease of outgoing solids. There are two possible contributing factors to these results. The first is the already mentioned unfavorable moisture profile and the second is an inadequate pressure impulse. A similar decrease of steaming efficiency with increasing ingoing solids was reported in [5].

3.2 Mechanical Properties

3.2.1 Sheet Densification

A number of researchers have produced results which show that increased sheet temperature during wet pressing results in increased fiber bonding and, as a result, greater densification of the sheet [6, 7, 8]. Greater densification generally results in greater sheet strength.

In this experiment, apparent sheet density prior to drying was used as a measure of sheet densification. The apparent sheet density was determined using the sheet oven-dry weight and the soft-platen caliper measured immediately after MTS pressing. Average values of apparent density for all the cases are given in Figure 5. The increase in apparent density over the case of no steaming is shown in Table 3.

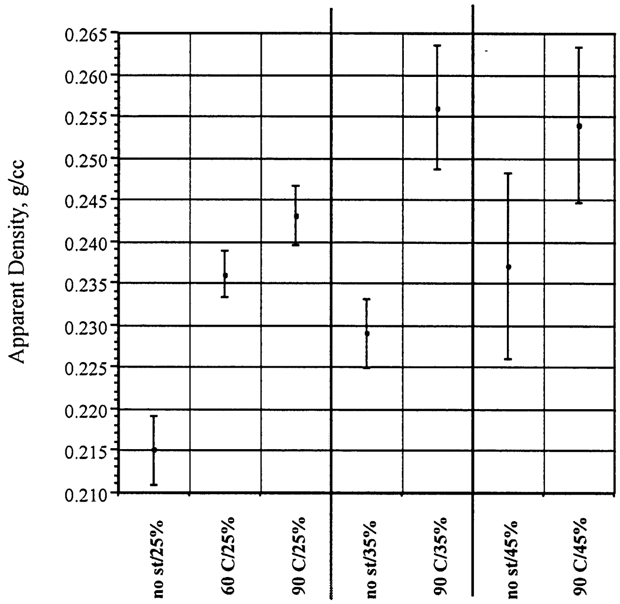


Figure 5. Apparent Density

Solids	Increase in Apparent Density Relative to No Preheat	
	Total Increase (g/cm^3)	Percent Increase
25%	0.028	13.0%
35%	0.027	11.8%
45%	0.017	7.2%

Table 3. Increase in Apparent Density Prior to Drying - 90°C Steaming Case

It is seen that steaming noticeably increases densification for all cases. Also, the amount of densification decreases with increasing solids. The densification is in general attributed to increased conformability of the heated fibers and lower springback due to steaming. The solids effect is probably due to both the decrease in flexibility of the fibers with lower moisture content and the effects of previous pressings.

Figure 6 shows the apparent density for the sheets after drying (calculations based on weight and caliper of dried and conditioned sheets). Note that the densities are all higher, by almost a factor of 2, than the densities shown in Figure 6. Also, the density changes are significantly less than those for the wet sheets. Thus, the drying contributed significantly to the densification. The changes are quantified in Table 4.

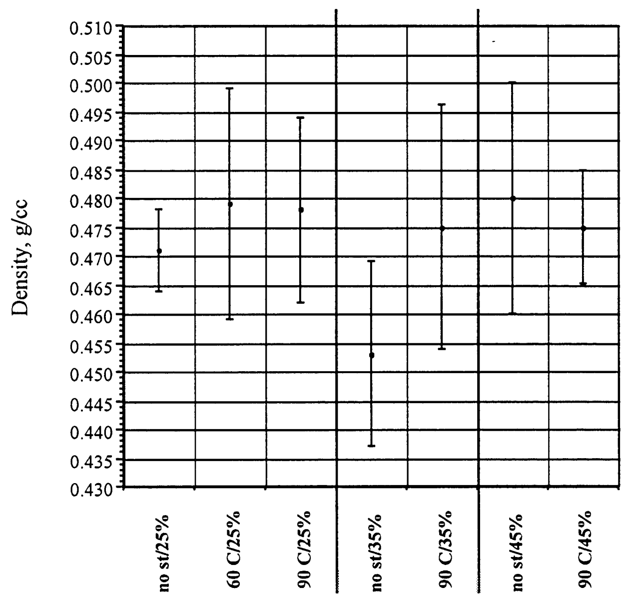


Figure 6. Conditioned Apparent Density

Solids	Increase in Apparent Density	
	Total Increase (g/cm^3)	Percent Increase
25%	0.007	1.5%
35%	0.022	4.8%
45%	- 0.005	- 1.0%

Table 4. Increase in Apparent Density Conditioned Sheets - 90°C Steaming Case

An unexplained feature of these results is that the conditioned density for the 35% solids, no preheat case, is less than that for the 25% solids, no preheat case. It would normally be expected that the 25% sheets would have the lower density. The results may be an artifact of how the sheets were prepared (25% sheets were not prepressed, 35% sheet were prepressed) and an interaction with the drying process. A further explanation is not possible with the current data. The improvement in density for the 35% solids case is 6%, which is of the same order as reported in [9, 10].

3.2.2 STFI Compression Index

Figure 7 shows the average CD STFI Indexes for all the cases, including the prepressed sheets. The results are interesting for a number of reasons.

Examining the 25% solids results, it is seen that the sheets heated to 90°C had the highest STFI Index. The sheets heated to 60°C had almost the same index as those that were not heated. Referring back to Figure 4, the sheets heated to 60°C had higher water removal than those heated to 90°C. This suggests that there is not a direct relationship between water removal, strength increase, and sheet temperature. Perhaps in the case of sheet strength moisture profile plays less of a role than it does in water removal. The 35% solids case provides additional support for this argument. The 90°C case yielded little or no increase in water removal over the case of no heating, yet there was an increase in the CD STFI Index. Additional data is required for any definitive conclusions.

The 45% solids case is interesting because there was virtually no difference between the prepressed, no heat, and 90°C cases. This, combined with the water removal data, suggested that the pressing profile used had no significant effect on the sheet. It provides added support for the idea that the pressing pulse was of inadequate magnitude for the solids content of the sheet.

Average values of geometric mean of STFI Index are shown in Figure 8. While there is a slight trend towards increased index values with heating to 90°C, the statistical significance of the results is limited.

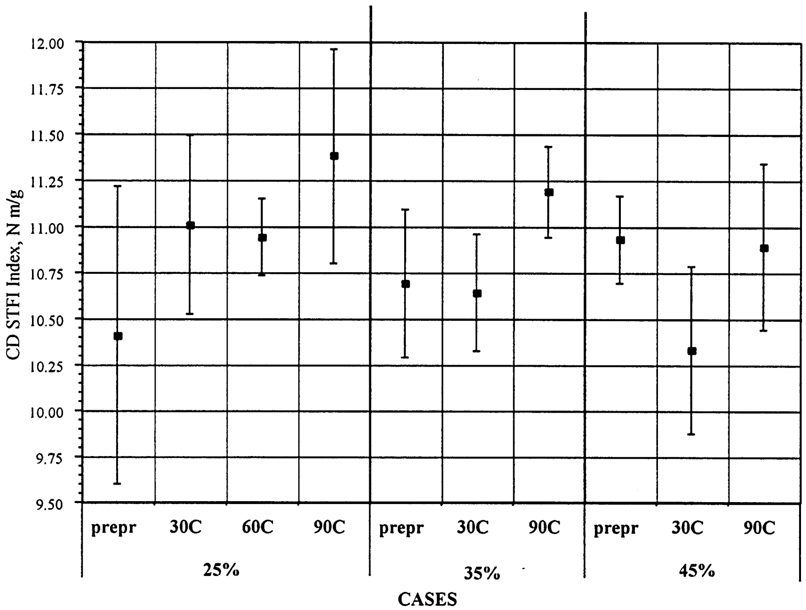


Figure 7. CD STFI Index

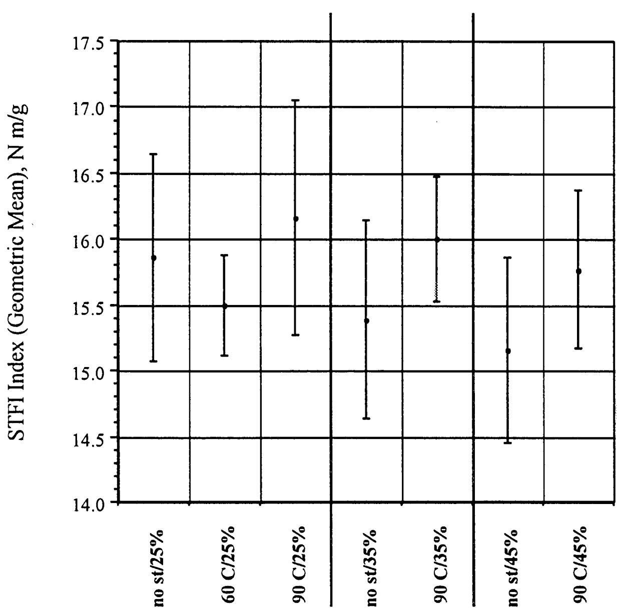


Figure 8. Geometric Mean STFI Index

3.2.3 Specific Elastic Modulus (SEM)

Mechanical strength of the sheets was also characterized by specific elastic modulus (SEM). SEM was measured using an out-of-plane (z-direction) ultrasound tester. The average values are plotted in Figure 9.

Figure 9 shows that the maximum SEM is obtained at an ingoing solids of 25% and an ingoing temperature of 90°C. Given that SEM decreases or remains unchanged for all other cases it appears that specific, but as yet not fully determined, conditions are required to obtain an increase in SEM. The results are similar to those for CD STFI in that a case which did not produce maximum water removal (25% solids, 90°C) did produce a maximum strength increase. This once again brings up the question of what is the effect of temperature profile, moisture profile, sheet solids, and pressing impulse on final water removal or strength increase.

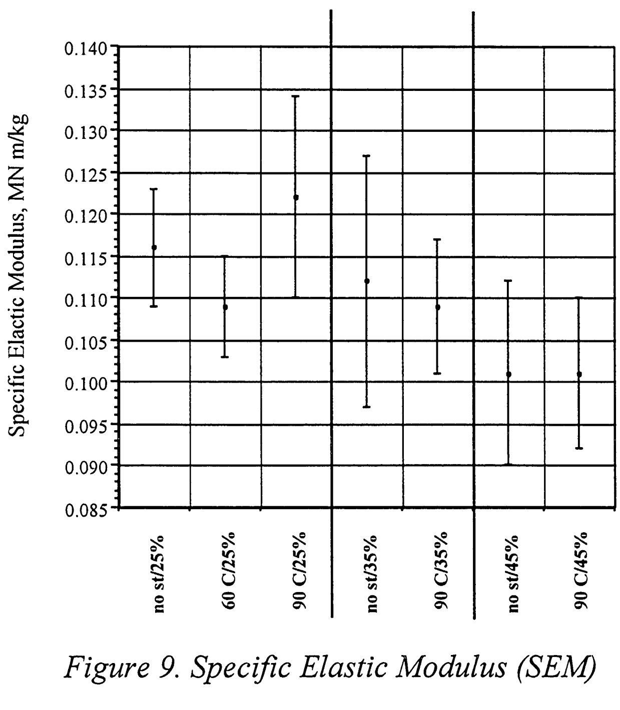


Figure 9. Specific Elastic Modulus (SEM)

3.3 Air permeability prior to and after MTS pressing.

The key to using steam as an energy transfer medium is that it must be condensed in the sheet [2]. The condensing rate is determined by the condensing surface available and the temperature of that surface. A sheet with high permeability will allow the steam to penetrate deeper into the sheet. Thus, a greater amount of steam is condensed due to the greater surface area exposed to the steam. In addition, a more even temperature profile is produced [11].

Average values of air permeability for each case, including prepressed cases, are shown in Figure 10. It is interesting that for the prepressed sheets air permeability at a solids level of 25% is only slightly lower than at 45% solids. MTS pressing without steaming resulted in a significant increase in the air permeability of the pressed sheet, especially at ingoing solids of 45%. Steaming resulted in a significant decrease in air permeability. The steam heating process and subsequent pressing had a definitive effect on air permeability. A summary of the changes is shown in Table 5. Table 5 and Figure 10 show that there is an interrelationship between sheet solids, sheet heating, and resultant air permeability. As solids increase, resultant sheet air permeability increases under the no preheating condition. Preheating tends to decrease air permeability, but that trend decreases as the sheet solids increases.

Solids	Ambient - Prepress		90°C - Prepress	
	Actual ($*10^{12}$ m^2)	%	Actual ($*10^{12}$ m^2)	%
25%	+0.070	+63.0	-0.090	-81.0
35%	+0.065	+33.0	-0.050	-28.5
45%	+0.190	+165	+0.055	+47.8

Table 5. Change in Air Permeability from Press Condition

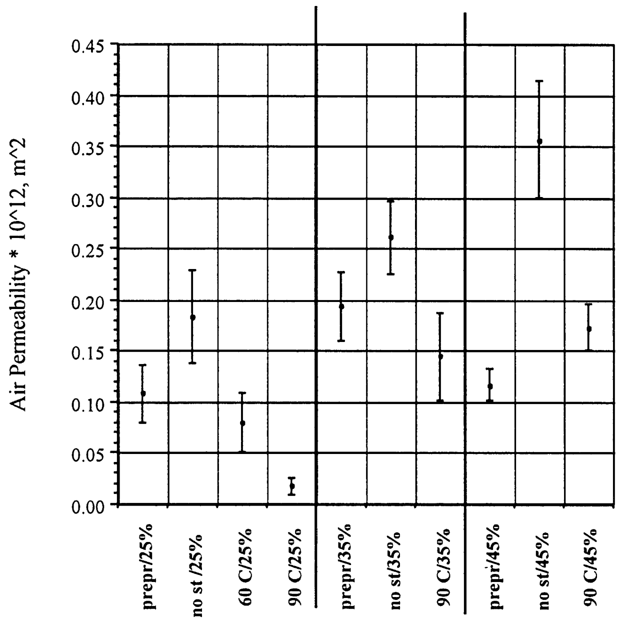


Figure 10. Air Permeability

4. CONCLUSIONS

The effect of ingoing sheet solids and temperature on water removal and sheet mechanical strength was addressed in this work. The pressing pulse was kept constant and corresponded to the level of a 1st or 2nd press.

Summarized data of average values (bold fonts), standard deviations (plain fonts) and percentage of base line case - no steam /25% (plain underline fonts) are tabulated in Table 6 at the end of this section. Using that table and the data presented in this report, a number of conclusions can be made. These are listed below.

Water removal

1. Preheating - Water removal can be significantly increased by employing sheet preheating.
2. Sheet moisture profile - A moisture profile in which the top of the sheet (press side) is wetter than the bottom side (felt side) is detrimental to water removal. A uniform moisture profile is less detrimental to water removal.
3. Sheet solids - as solids level increases, water removal decreases for the same pressure pulse. The effect of sheet moisture profile also increases as sheet solids increase.

Sheet Strength

1. Preheating - Sheet strength, as quantified by STFI Compression Index, Specific Elastic Modulus, and apparent density can be increased by employing preheating.
2. Correlation with water removal - Sheet strength changes do not necessarily follow the same trends when sheet heating is employed. There can be no significant change in water removal yet be a significant increase in sheet strength.
3. Self correlation - The factors used to measure sheet strength, STFI, SEM, and density do not follow exactly the same trends. This is undoubtedly due to the difference in properties measured by each method.
4. Pre and post drying - Drying can affect densification; it tends to "smooth out" the effects of different sheet preheating conditions.

Permeability

1. Air permeability - Preheating tends to decrease sheet air permeability, although the effect decreases with increasing solids level.
2. Specific Surface - The specific surface of sheets, as determined by water permeability tests, tends to decrease with increasing solids contents.

	25%			35%		45%	
	No steam	60°C	90°C	No steam	90°C	No steam	90°C
Ingoing Solids, %	**25.64** 1.2	**24.51** 0.81	**25.2** 0.95	**35.24** 1.24	**35.73** 1.46	**44.1** 1.58	**43.54** 1.76
Outgoing Solids, %	**31.89** 0.9	**34.05** 0.81	**32.66** 0.55	**37.83** 0.69	**38.63** 1.02	**44.38** 1.47	**43.03** 1.37
Increase in Dryness, %	**6.25** 100	**9.54** 152.6	**7.46** 119.4	**2.63** 42.1	**2.90** 46.4	**0.28** 4.48	**-0.51**
OD Basis Weight, gsm	**210.6** 10.3 100	**202.3** 9.2 96.1	**209.4** 8.3 99.4	**208.1** 7.1 98.8	**209.7** 7.9 99.6	**202.3** 9.6 96.1	**198.4** 8.1 94.2
Peak Pressure, psi	**938.9** 39.9 100	**888** 37.7 94.6	**878.6** 29.3 93.6	**931.3** 44.1 99.2	**900** 46.1 95.9	**899.6** 56.3 95.8	**881** 51.2 93.8
Pressure Imp, psi sec	**7.313** 0.333 100	**7.029** 0.194 96.1	**7.035** 0.18 96.2	**7.201** 0.237 98.5	**7.03** 0.208 96.1	**7.057** 0.287 96.5	**7.009** 0.243 95.8
Density, g/cc	**0.471** 0.007 100	**0.479** 0.021 101.7	**0.478** 0.016 101.5	**0.453** 0.016 96.2	**0.475** 0.021 100.8	**0.48** 0.02 101.9	**0.475** 0.01 100.8
SEM, km^2/sec^2	**0.116** 0.007 100	**0.109** 0.006 94	**0.122** 0.012 105.2	**0.112** 0.015 96.6	**0.109** 0.008 94	**0.101** 0.012 87.1	**0.101** 0.009 87.1
Apparent Density just after Press, g/cc	**0.215** 0.0042 100	**0.236** 0.0028 109.8	**0.243** 0.0035 113.0	**0.229** 0.0041 106.5	**0.256** 0.0075 119.1	**0.237** 0.0111 110.2	**0.254** 0.0093 118.1
STFI Index MD N m/g	**22.84** 1.271 100	**21.95** 0.697 96.1	**22.94** 1.368 100.4	**22.25** 1.765 97.4	**22.89** 0.906 100.2	**22.24** 1.101 97.4	**22.84** 0.794 100
STFI Index CD N m/g	**11.01** 0.482 100	**10.94** 0.208 99.4	**11.38** 0.579 103.4	**10.64** 0.319 96.6	**11.19** 0.245 101.6	**10.33** 0.455 93.8	**10.89** 0.448 98.9
STFI Index GM N m/g	**15.86** 0.783 100	**15.5** 0.381 97.7	**16.16** 0.89 101.9	**15.39** 0.751 97	**16** 0.471 100.9	**15.16** 0.708 95.6	**15.77** 0.597 99.4
Apparent Relat Compression	**0.152** 0.0234 100	**0.19** 0.0198 125	**0.217** 0.0234 142.8	**0.094** 0.0065 61.8	**0.194** 0.01 127.6	**0.107** 0.0113 70.4	**0.192** 0.0163 126.3
Air Permeab *10^12,m^2	**0.183** 0.0452 100	**0.0794** 0.0291 43.4	**0.0174** 0.0078 9.51	**0.261** 0.0351 142.6	**0.145** 0.0425 79.2	**0.356** 0.0572 194.5	**0.173** 0.023 94.5
Air Per Prepr *10^12, m^2	**0.108** 0.0279 59			**0.1936** 0.0332 105.8		**0.1168** 0.0153 63.8	

Table 6. Summary of Results

5. REFERENCES

1. Patterson, T.F., Iwamasa, J.M., Project F002. Progress Report to the Member Companies of IPST - Report 1 (August 1997)

2. Cutshall, K., and Hudspeth, D., 1993 Practical Aspects of Pressing and Drying Seminar, TAPPI Notes, 229-240.

3. Szicla, Z., and Paularupo, H., Changes in Z-Direction Density Distribution of Paper in Wet Pressing. J. of Pulp and Paper Science: Vol. 15, No.1, January 1989, J11-J17.

4. Wahlstrom, B., Our Present Understanding of the Fundamentals of Pressing.,Pulp and Paper Magazine of Canada, October 3, 1969, 76-96.

5. Royo, M., and Thorp, B., The Effect of Direct Steam Heating on Water Removal, PIMA, September 1981, 38-41.

6. Back, E., Consolidation - The Future - Including Hot Press Nips, Preprint of XVII EUCEPA Meeting, Vienna 1977, 248-255.

7. Back, E., Steam Boxes in Press Sections - Possibilities and Limitations, Appita 41, May 1988, No.3, 217-233.

8. Back, E., Using the Wet Press to Optimize Paper Properties. PTI, April 1987, 453-459.

9. Kaljunen, R. and Kaasalainen, H. Increasing Sheet Temperature in Press Improves Drainage, profile. #5, 1980

10. Engineering & Design Developments in Press Section Operation, Lehtinen, A., Paper Age p. 32-33 (November 1979).

11. Patterson, T.F., Iwamasa, J.M., Project F002. Progress Report to the Member Companies of IPST - Report 4 (September 1997)