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The Effects of Base Sheet Moisture Content on Size Penetration Characteristics

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A Thesis Submitted by:
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Table of Contents

Page No.

ABSTRACT:

This thesis was designed to determine the effects of moisture on the penetration of size solution into a paper sample. The experiment involved use of laboratory equipment and procedures to accomplish the objectives of this experiment.

Handsheets were conditioned, sized, cut, stained, and viewed under a laboratory microscope to obtain the desired results. The results from this procedure determined that the area of size deposition was dependant upon the moisture content of the paper sheet. As the moisture content of the samples increased, the size was retained more on the sample's surface as opposed to penetration into the paper web.

If the results obtained in this study can be reproduced on the machine scale, extensive capital benefits will be realized by the particular mill. The benefits will be in the form of increased production as well as a reduction in steam consumption. However, benefits obtained from this increase in moisture should be weighed against effects on strength as well as other problems associated with high moisture content utilization, such as moisture profile.

INTRODUCTION:

This project was designed to investigate the effects of moisture content on the penetration characteristics of surface sizing. Laboratory experimentation was performed in order to determine the moisture content for development of optimum surface sizing of the paper sheet. Laboratory procedures included application of starch size to handsheets, porosity analysis, staining of the starch component, microscopic analysis of penetration into the tested sheet, and Hercules size test. This project was performed in conjunction with an analysis of wet pressing (density) variation on the penetration characteristics.

Handsheets used in this analysis were conditioned to moisture content levels of 1.98%, 5.15%, and 7.24%. A hydroxy ethyl ether starch (Penford Gum 280) was applied to the handsheets in a size press simulation. The handsheets were then cut so that the cross-section could be adequately analyzed, and the starch component was stained with iodine vapor for identification purposes. An electron microscope was then utilized to determine the depth and other penetration characteristics. These processes were used in the determination of the optimum pre-size press moisture content for surface sized papers.

BACKGROUND:

The cited literature mentions that the typical moisture content before the size press ranges from below 1% to a high of 12%, with no indication of which is more beneficial for surface sizing properties. Jones (1) points out that the bulk of fine paper mills operate in the range of 1% to 3% moisture content into the size press. This low moisture content is maintained in order to produce a more constant moisture profile into the size press. The moisture profile is needed to prevent uneven absorption of the size solutions at the size press. Uneven absorption can ultimately result in variable cross-machine starch pick-up and reel building problems. However, operation at higher moisture can be used if the moisture profiles are more consistently regulated and adjusted. These higher moisture contents can have a direct impact on a considerable steam use reduction as well as an increase in machine speed and production (1).

Reasons For Surface Sizing:

The process of surface sizing on a paper machine (at the size press) is done to fill in the voids in the paper sheet, reducing pore radius and, therefore, the rate of liquid penetration. This process is often accompanied by applying an internal size at the wet end of the paper machine in order to increase the contact angle between the paper and the penetrating liquid. Internal sizing is performed with rosin addition on the wet end, while surface sizing uses a starch application at the size press (2).

There are many advantages associated with surface sizing as opposed to internal sizing, and are listed below:

- more specific action; optimum control
- less sensitive to changes in wet-end operations
- 100% retention of additive
- reduction in wet-end deposits
- increased press clothing life due to lower deposits
- improved paper quality

Mechanism of Absorption:

There are many factors that influence the absorption of liquid solutions into the paper structure. The amount of surface sizing absorbed, as well as the depth of penetration, is determined by factors such as paper resilience, internal sizing, and pore structure (3). The pore structure of the sheet can be used to predict the absorption of size as described in the Lucas-Washburn equation:

$$L^2 = \frac{\sigma R (\cos \theta)\, t}{2\eta}$$

Where:
t = time
η = fluid viscosity
R = capillary radius
θ = contact angle
σ = surface tension of fluid
L = depth of fluid penetration

This equation indicates that penetration is influenced by both the size of pores and the surface characteristics of the fibers. Alteration of the contact angle (θ) is often done by addition of internal size on the wet end of the paper machine (4). Experimentation has been done by Brecht that indicates that an increase in moisture content will increase the pore size and, therefore, increase the length of penetration in a given time. The time for size penetration is very limited because of the subsequent fast drying in the post size-press dryers.

Salminen indicates that there are characteristics of paper that distinguishes it from the Lucas-Washburn model. These factors include: 1) Time and velocity dependence of dynamic capillary pressure, 2) Counter pressure of air, and 3) Expansion of fiber network and fiber sorption. In many dynamic wetting situations, the transport of air is restricted, and a counter pressure is caused by trapped air. It was also stated that the presence of water can affect the transport velocity as well as the cross section of the penetrating water front. The influence on transport velocity is related to moisture's influence on capillary radius and viscous drag. In addition to the Lucas-Washburn variables, these considerations must be looked at as factors affecting fluid penetration characteristics into the paper web.

In Salminen's investigation, there seems to be many conflicting phenomena in which the moisture content seems to influence the penetration of fluids into a paper surface. Absorbed water particles on the fiber surface should increase the attraction forces between the fluid and fiber surfaces. Because of this, a decrease in moisture content should reduce the dynamic capillary pressure and the transport velocity. However, a decrease in moisture would also increase the difference in osmotic pressure differential between the interior and exterior of the fibers giving increased transport rate. The influence of moisture content on pore structure is very limited because of existing expansion taking place during the penetration of the size solution, however, this factor must be considered because of the effects of viscous drag and cross section of the water front (5). One of the objectives of this project is to determine the dominating mechanism, if one exists, in the absorption of the size solution.

Moisture Effects on Sheet Properties:

The effects of varying moisture content has also been seen to affect the strength properties of the final sheet. The over-drying of the paper sheet causes it to become brittle. The results of a study by Granger (6), indicate that the paper properties were affected with varying moisture contents before the press section. His results show that brightness and tensile decreased while burst, tear, and fold increased. Granger's analysis showed that there are many other considerations to contemplate before altering your moisture values before the size press. The assumption should not be made that the 'most convenient' moisture for operators is the best parameter for the specific process.

A study by Durfy (7) suggests that the greater amount of starch lying on the paper surface -- the greater the strength properties including tensile, burst, and stiffness. This study, as well as other studies in this area, indicate that the greater the moisture content the greater the starch pick-up. However, the studies also indicate that the sizing performance at these higher moisture was limited because the size is deposited further into the paper sheet as opposed to the dry sheets where the size is deposited on the surface.

EXPERIMENTAL APPROACH:

Laboratory work was carried out to determine the affects of varying base sheet (handsheet) moisture content on the depth of applied size penetration. A typical furnish mix of 75/25 softwood to hardwood was refined in a Valley beater to a target Canadian Standard Freeness of 500 ±10 ml. Handsheets were then constructed on the Noble and Wood handsheet maker to a target weight of 5.0 ±0.25 grams. The relatively high weight of the base sheet was used to prevent size penetration through the entire base sheet structure. A total of 180 handsheets were constructed using three different wet pressing loads. The completed handsheets were then conditioned according to TAPPI standards and tested for caliper as well as porosity values.

Moisture Manipulation:

To obtain the levels of moisture content, three sets of sixty handsheet were subjected to different environmental conditions. Oven drying for one hour followed by placing the sheets in a desiccator until size application was performed to produce the 'low' moisture samples (1.98% M.C.). Another set of samples was conditioned at 50% Relative Humidity, and 73^{0}F according to TAPPI standards (T-402). The conditioning produced a final moisture content of 5.15%. The final set of samples was placed in an enclosed environment with several water saturated towels which produced a final moisture content of 7.24%.

Starch Preparation:

By suggestion of a faculty member, a hydroxy ethyl ether starch (Penford Gum 280) was used for size press application. The starch solution was diluted to 7% solids by assuming a starch moisture content of 10%. The starch solution was then cooked according to the following procedure.

1. Obtain 1 Liter stainless steel beaker and dial thermometer.
2. Weigh out needed amount of 'dry starch' for mixture of 7% solids.
3. Stir in corresponding amount of water to dilute to 7% solids.
4. Warm up beaker to 85-90^{0}C (185-194^{0}F) for 30 minutes.
5. Maintain temperature at 65^{0}C (150^{0}F) with slight stirring for application.

Size Application:

The application of the starch size solution was done using a laboratory wax applicator. This applicator is characterized by two steel rolls, one of which is submerged in the starch solution and one a backing roll. The paper sheet is passed through these two rolls and size is applied to the applicator roll side. The application was done on the felt side of the sample handsheets in order to keep this variable constant. After the size was applied, the handsheets were passed once through the Noble & Wood handsheet dryer for size curing.

Sample Cutting:

After the samples were sized and subsequently dried, representative handsheets were selected. These selected handsheets were used in the remainder of the penetration analysis. Handsheets were selected based on the uniformity of size application, representative porosity values, and formation.

The selected handsheets were then cut by two differing methods; sandpaper and razor blade cut. Two different cutting operations were performed because it was not evident that which of these methods would give a good 'clean' cut without distortion of the sheet structure. The sandpaper was used along with two pieces of metal. These metal pieces were used to keep the angle of cut constant (50^0 from paper plane) as the sheet was passed over the sandpaper. The reason for cutting the samples on an angle was so the cross-section of the paper sample could be viewed more easily under the microscope. A similar arrangement was used in the sample cutting with the razor blade, where the cutting angle was held constant (30^0 from the paper plane) with the metal guide.

Starch Staining:

In this analysis, it was necessary that the starch fraction of the samples be identified in some way to distinguish it from the fiber fraction of the paper samples. Iodine vapor was used to provide a distinct and selective identification of the starch fraction. The procedure consisted of isolating the vapor in a confined space (in this case, an acrylic scale cover about $4ft^3$ in volume) along with the paper samples. The samples were first placed in the confined space with the addition of steam in order to moisturize the samples, this was done for two minutes. Iodine crystals were then placed on the steam bath which produced an emanating purple vapor. This vapor is highly attracted to the starch fraction, hence the starch staining. The samples were allowed to equilibrate in the iodine vapor for 1.5 minutes for complete coloring of the size component. This method of identification of the starch fraction proved to be very effective.

Structure Analysis:

Viewing of the sample cross-sections was performed with the aide of an electron microscope. The pictures (seen in Figures 1, 2, and 3) were obtained from the video printer installed on this microscope. The magnification setting used during the analysis was 4/.10. During the analysis, the samples were placed between two slide glasses for viewing of the previously cut edge. The microscope was adjusted and focused until the cross-sectional image became clear. The image was then printed using the video printer.

RESULTS:

This project was done in conjunction with an analysis of wet pressing variation on size penetration and migration. This is the reason for identification of different press loadings in Figures 1, 2, and 3. As seen in the pictures presented in the Figures 1, 2, and 3, the paper cross-sectional structure can be seen as the white-orange spotted surface along with the black portion.

This black layer on the paper surface is the purple stained sizing present on the paper surface. The distances of starch penetration were estimated by using caliper measurements and correlating them to the segmented scale seen on the pictures.

As seen in Figure 1 (at low wet pressing) the high moisture content samples (7.24% M. C.) exhibited an estimated penetration distance of 2.0/1000" (two one-thousandths of an inch). The starch penetration occurring in the medium moisture (5.15% M. C.) samples were estimated at about 2.5/1000". Finally, the highest depth of penetration, 3.0/1000" was realized under the low moisture content of 1.97%.

In Figure 2 (medium wet pressing conditions), the high moisture samples exhibited an estimated size penetration of 2.25/1000", medium moisture samples 1.75/1000", and low moisture at a depth of 2.25/1000". These measurements show that the high and low moisture samples exhibited very little difference, if any, in depth of size penetration.

Figure 3 (high wet pressing conditions) shows a very shallow depth of penetration on the high moisture content samples, about 1.0/1000". The depth of penetration was increased to 2.0/1000" and 2.75/1000" in the medium and low moisture content samples respectively. These results indicate that the size penetration depth increased as the moisture content decreased.

Figure 1
(Low Wet Pressing)

High Moisture | Medium Moisture | Low Moisture

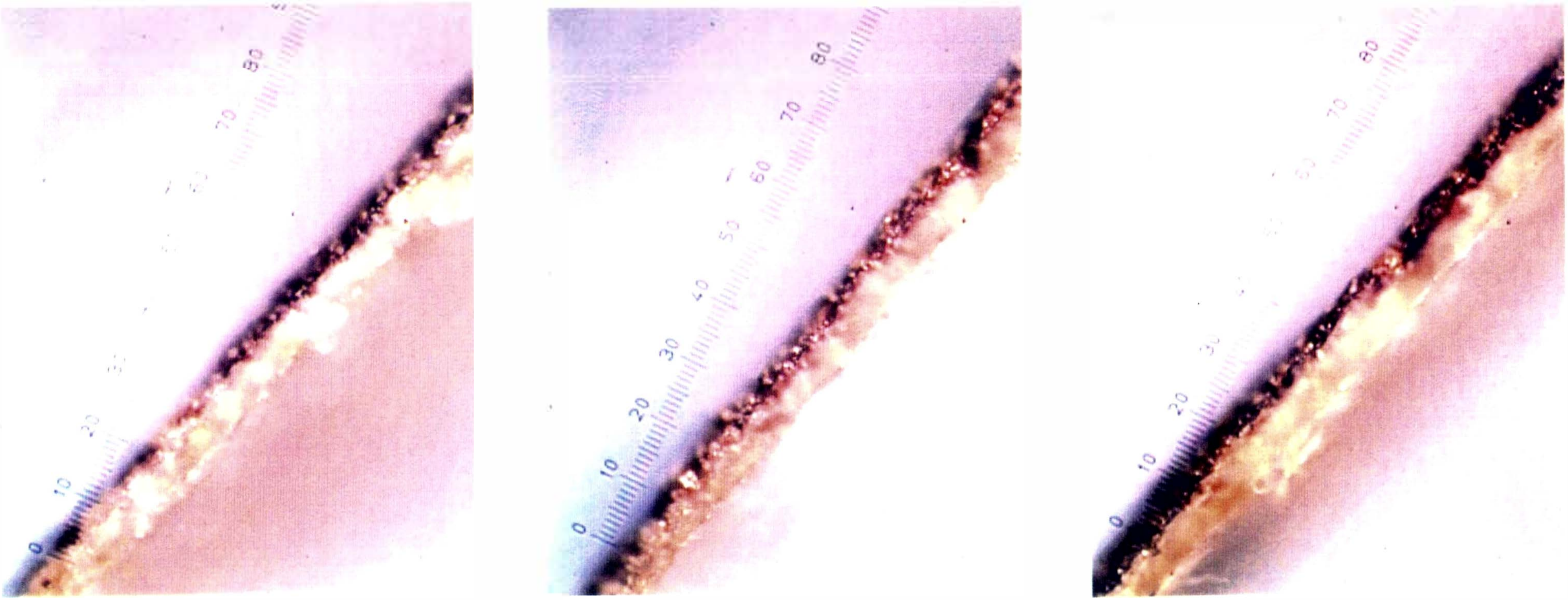
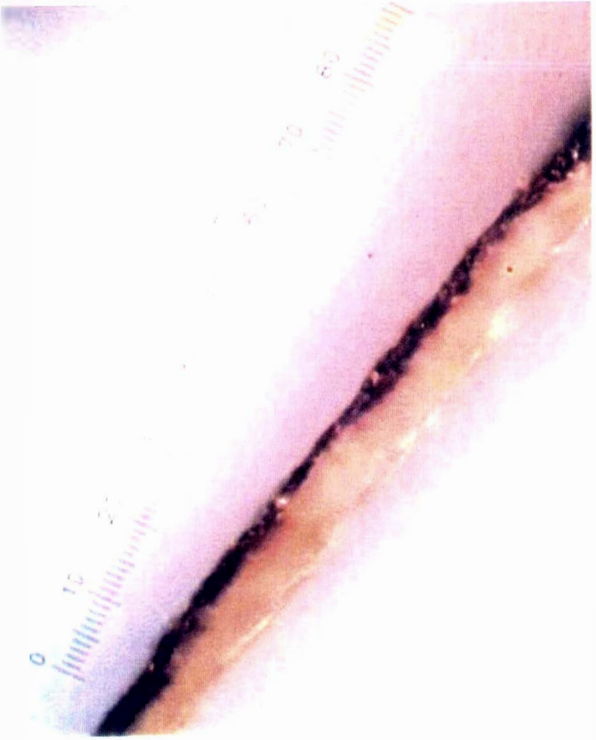
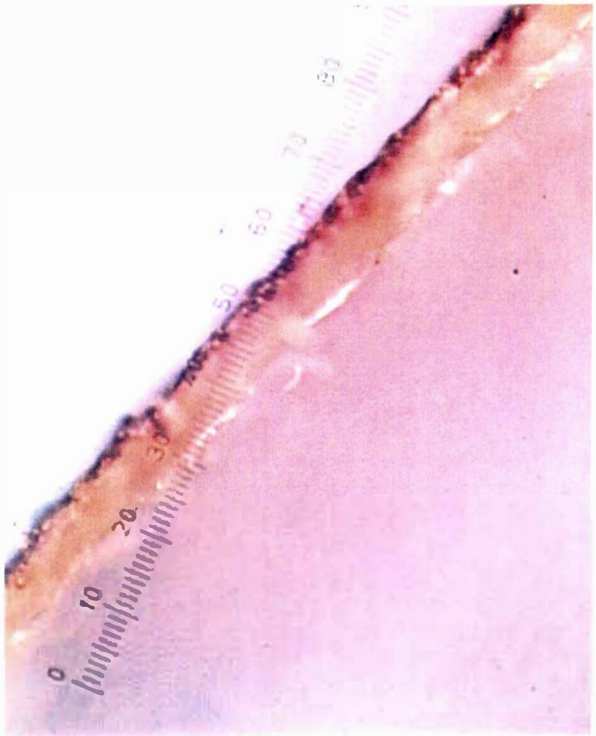


Figure 2
(Medium Wet Pressing)

High Moisture



Medium Moisture



Low Moisture

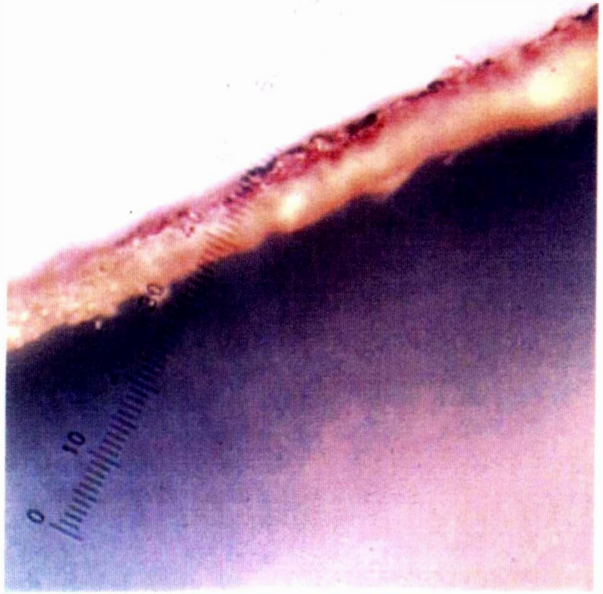
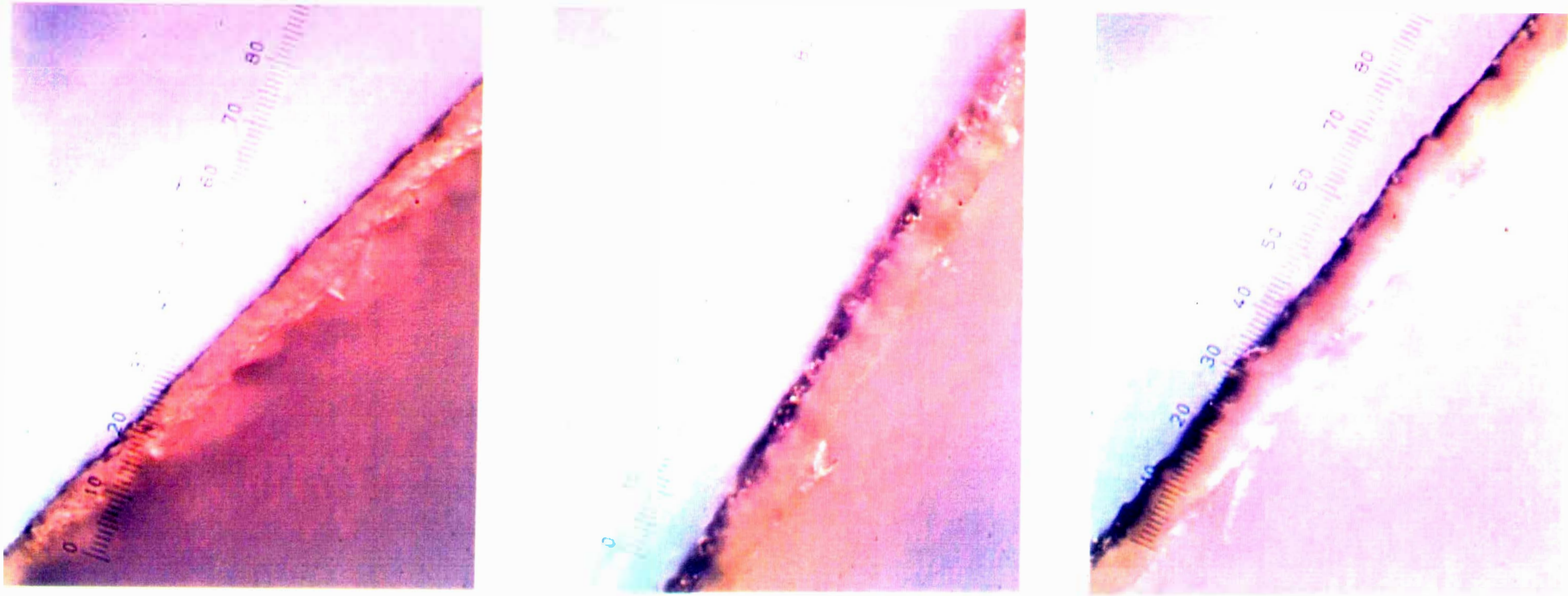


Figure 3
(High Wet Pressing)

High Moisture   Medium Moisture   Low Moisture



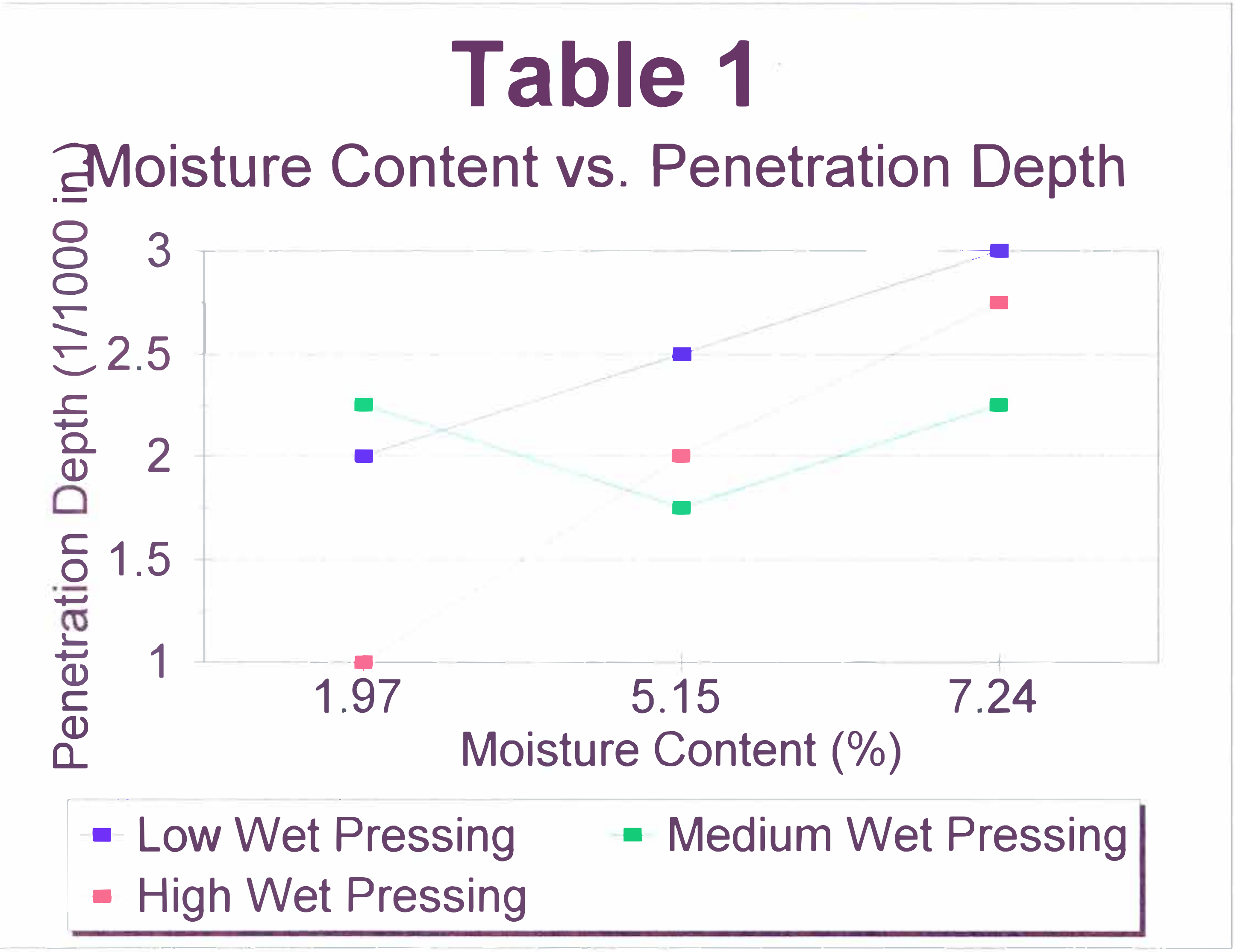


Table 1
Moisture Content vs. Penetration Depth
Penetration Depth (1/1000 in.)
3
2.5
2
1.5
1
1.97
5.15
7.24
Moisture Content (%)
Low Wet Pressing
Medium Wet Pressing
High Wet Pressing

DISCUSSION:

The results of the experimentation portion of this project indicate that an increase in moisture content of the paper samples caused the size fraction to be deposited on the surface of the paper sample. This trend was apparent on two out of the three samples that were examined. In the sample that did not exhibit an apparent trend, the high and low moisture samples showed about the same depth of penetration. This raises some doubt about the reproducibility of the trends that were observed.

There are a number of mechanisms that would cause the size to deposited on the paper surface with increased moisture. As stated in the BACKGROUND portion of this paper, there are also arguments for surface size deposition with low moisture contents. The goal of this thesis was to analyze the results and hypothesize about the dominant mechanisms occurring with changing moisture content. The prediction of a dominant absorption mechanism is very difficult because of limitations in measuring these mechanisms. However, the hypothesis of how these mechanisms may have been affected is better suited for this level of study.

The presence of the increased moisture in the paper sheet may cause the pores to swell and create a reduction in the capillary radius. This reduction in capillary radius would affect the penetration of liquid, as stated in the Lucas-Washburn equation (see BACKGROUND pg. 5). The viscous drag between the two liquid surfaces may have also had an impact on the decrease in penetration depth with higher moisture contents. As stated by Salminen, a decrease in moisture content increases the moisture concentration gradient and the osmotic pressure differential between the interior and exterior of the fibers. Therefore, the water transport rate is increased by a reduction in moisture content (5).

CONCLUSIONS:

The results of this project show that an increase in moisture content will result in deposition of the size fraction on the surface of the paper as opposed to penetrating into the paper structure, as was seen in low moisture content samples. These results indicate that further research should be done in this area in order to evaluate the effects of moisture content on size penetration on actual mill scale machine conditions. The results of this experiment were obtained on a laboratory scale as opposed to the full scale mill environment.

If these results are consistent with actual mill trials, many possible benefits may result. The operation at higher moisture contents before the size press offers the ability to increase production on machines that are dryer limited. This is done by reducing the amount of dryer residence time needed to produce the desired moisture content. In machines that are not dryer limited, a considerable amount of steam could be saved with an increase in size press moisture content. A calculation made by Jones states that if a machine producing 100 tpd would increase the moisture content before the size press by one percentage point, the yearly savings would be as high as $432,000 (1).

Caliper Data

High Moisture Samples
Data Compiled: March 14, 1995

No.	High Pressing	Med Pressing	Low Pressing
1	8.5	9.7	8.5
2	8.4	9.7	8.9
3	8.3	8	9.2
4	8.3	8.8	8.5
5	8.2	8.2	8.3
6	8.4	8.3	8.3
7	8.5	8.4	8.8
8	8.4	8.2	9.2
9	8.2	8.9	9.2
10	8.1	8.2	9.4
11	8.5	8.2	8.8
12	8.6	7.9	9.3
13	8.8	8.2	8.7
14	8.8	8.3	9
15	8.7	8.2	8.7
16	8.8	8.3	8.6
17	8.9	8.4	8.7
18	9.3	8.2	8.6
19	8.1	8.6	9.1
20	8.6	8.4	9.4
21	8.3	8.2	8.5
22	8.5	8.3	9.3
23	8.5	8.2	9
24	8.5		8.9
25	8.5		9
26	7.5		9
27			10
28			
29			
30			
Avg.	**8.469231**	**8.426087**	**8.922222**

Medium Moisture Samples
Data Compiled: March 14, 1995

High Pressing	Med Pressing	Low Pressing
7.7	8.2	8.1
7.7	8.6	8.4
7.8	9.1	8.6
7.7	8.8	8.5
8	8.9	8.3
7.8	8.5	8.4
7.8	8.8	8.8
7.7	8.7	7.8
8	9	8.6
8.2	8.9	8.3
8	8.5	7.9
8	8.9	8.4
8.2	8.6	8.8
8.1	8.8	8.7
8.1	8.7	8.4
8.2	8.5	9
8.3	9.1	9.4
8.5	8.7	9.6
7.7	8.4	8.9
7.6	8.2	9
7.7	8.3	8.9
7.7	8.7	9
7.4	8.6	9.2
7.5	8.7	8.9
		9.3
		8.8
		8.7
7.891667	**8.675**	**8.692593**

Caliper Data

Low Moisture Samples
Data Compiled: March 14, 1995

No.	High Pressing	Med pressing	Low Pressing
1	8.2	8.6	8.9
2	7.6	8.5	9
3	7.5	8.8	8.6
4	7.8	8.7	8.5
5	8	8.4	8.7
6	8	8.3	8.7
7	8.1	8.3	8.5
8	8.7	8.5	8.6
9	8.2	8.5	8.5
10	8	8.5	8.5
11	8.2	8.6	8.4
12	8.1	8.6	8.8
13	8.2	8.6	8.6
14	7.9	8.6	8.5
15	8	8.5	9
16	8.2	9	8.5
17	8	9	8.6
18	8	9	8.7
19	8.2	8.5	8.7
20	8.2	7.9	8.3
21	8.2	8.7	8.5
22	8.4	8.5	8.7
23	8.1	8.3	9
24	8.1	8.1	9
25			8.7
26			8.7
27			8.7
28			9.1
29			8.6
30			
Avg.	**8.079167**	**8.541667**	**8.675862**

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