4-1992

Green Liquor Pulping for Corrugating Medium

Michael Thompson
Western Michigan University

Green Liquor Pulping for Corrugating Medium

By

Michael Thompson

Paper 472, Senior Engineering Problem

Advisor: Dr. Shiver

Western Michigan University

Date: 04/29/92

ABSTRACT:----------

24 pulping runs for producing corrugating medium were conducted with various chemical concentrations of sodium carbonate and sodium sulfide (green liquor). All other pulping variables were held constant. The results showed a linear relation between the amount of total alkali (on wood) and yield decrease at constant sulfidities. The results also showed the optimum sulfidity of the liquors to be 25%. The strength properties were only affected by the pulp yield and not by the amount of chemical concentration used to produce that yield.

TABLE OF CONTENTS

INTRODUCTION

The objective of this engineering problem is to optimize the chemical ratios used in green liquor semi-chemical pulping. First of all, it should be noted that the nomenclature applied to green liquor will be the same as that used for kraft pulping. The use of green liquor (GL) to produce semi-chemical pulp for corrugating medium started in the early to mid '70's. Green liquor has been used successfully to produce corrugating medium, and several facilities were converted from the neutral sulfite semi-chemical (NSSC) process to the GL process (3:109).

THEORETICAL DISCUSSION

RECOVERY CYCLE

The major thrust behind the conversion to GL from NSSC pulping was because of its superior chemical recovery cycle. The GL recovery process can be thought of as the kraft recovery process without the causticizing steps. The elimination of the causticizing cycle would eliminate the slaking, causticizing, calcining, and lime mud thickening and washing operations along with all of their inefficiencies. Of course the calorific value of semi-chemical liquors is much less than for kraft black liquor. But compared to the NSSC recovery process, GL pulping would eliminate the sulfur burner and carbonate crystallizer or the equivalent steps in NSSC mills using other recovery processes, with equivalent

spent liquor fuel value (3:324,4:113,8:1726). The GL recovery system would consist of the evaporators, recovery boiler, smelt tank, GL clarifier, GL storage, and GL dregs washer. Sodium sulfate would still need to be added to the recovery boiler as a make-up chemical.

LIQUOR COMPOSITION

The composition of green liquor from the kraft process consists mainly of Na_2CO_3 and sodium sulfide Na_2S, and NaOH is usually present from the dregs washing operation. To a much lesser extent, sodium will be present, as well as miscellaneous quantities of partially converted sulfur compounds (9:360). Although the chemical species present in green liquor, with the exception of NaOH if the mill is not combined with a kraft process, will remain the same, their relative concentrations will undoubtedly be varied for use as a pulping liquor. The sulfidity of the GL would need to expressed as the GL sulfidity instead of the traditional kraft white liquor sulfidity. For white liquor:

$$\% \text{ Sulfidity} = [Na_2S / (NaOH + Na_2S)] \times 100$$

For GL:

$$\% \text{ Sulfidity} = [Na_2S / (Na_2S + NaOH + Na_2CO_3)] \times 100$$

In both cases, all chemicals are expressed as Na_2O.

Effective alkali (EA) and active alkali (AA) will be expressed the same for GL as defined in the kraft process

$$EA = NaOH + .5\ Na_2S, \text{ as } Na_2O.$$

$$AA = NaOH + Na_2S, \text{ as } Na_2O.$$

It should be noted that while the sulfidity as expressed

for GL may not necessarily be much different than the sulfidity as expressed for WL, the ratio of sulfur to alkali will be much higher for the GL.

GL EQUILIBRIUMS

As with the kraft process, delignification in a GL process would be expected to depend on EA and sulfidity. Therefore the presence of EA and sulfidity should be studied under GL conditions.

As mentioned before, the EA is one half the sodium sulfide plus the sodium hydroxide present, both expressed as sodium oxide. Both sodium hydroxide and sodium sulfide are strong electrolytes, and hydrolize completely in water. These reactions will proceed as follows:

$$1)\ NaOH + H_2O \longrightarrow Na^+ + OH^- + H_2O$$

$$2)\ Na_2S + H_2O \longrightarrow 2Na^+ + S^{2-} + H_2O$$

The sulfide ion will then react with water by the equilibrium equation for hydrosulfide (HS^-) of :

$$3)\ S^{2-} + H_2O \Longleftrightarrow HS^- + OH^-$$

where, for S^{2-}/ HS^-

$$k = [HS^-][OH^-] / [S^{2-}]$$

Also possible is the equilibrium equation given by:

$$4)\ HS^- + H_2O \Longleftrightarrow H_2S + OH^-$$

where, for HS^-/ H_2S

$$k = [H_2S][OH^-] / [HS^-]$$

Since the hydroxyl ion (OH^-) is involved in reactions 3) and 4), these reactions will depend on the pH of the GL solution. It is known that in the pH range of 7 to 13 the hydrosulfide

ion (HS^-) is the dominate species. At the higher pH range the sulfide ion concentration increases, while at the lower pH range the hydrogen sulfide concentration increases, where the hydrogen sulfide is a dissolved gas. This indicates that the hydrosulfide ion will be the dominate species in a GL solution (9:362, 12:247).

The sodium carbonate should not play a direct role in pulping, but it should react indirectly. The expected reaction being:

$$5)\ Na_2CO_3 + H_2O \Longleftrightarrow 2Na^+ + CO_3^{2-} + H_2O$$

in equilibrium with,

$$6)\ CO_3^{2-} + H_2O \Longleftrightarrow HCO_3^- + OH^-$$

Reaction 6) would be expected to proceed only slightly as written, but it does imply that with the generation of acids during pulping reaction 6) would proceed to the right and act as a buffer for the GL. This buffering action would serve two purposes, the first of which is not letting the pH fall so low that hydrogen sulfide is generated. The other purpose being that alkali should continue to be available throughout the pulping cycle.

PULPING MECHANISMS

The reactions of hot alkali with lignin is the basis of alkaline pulping. The main reaction of hot alkali with lignin is the cleavage of beta-aryl ether linkages between the many phenol propane units. However, it has been shown that under soda pulping conditions (NaOH) the beta-aryl ether structures are converted to enol ether structures.

being cleaved.

A phenomenon that has been observed in soda pulping is the considerable decrease in reaction rate when about 85% of the lignin has been dissolved. Theory has it that some of the dissolved lignin groups condense onto the fibers and that these condensation products are very resistant to attack by alkali (9:380).

The kraft process employs hot alkali for delignification. Along with delignification, the alkali causes degradation of the carbohydrates found in wood including the different types of hemicelluloses and the cellulose. The reaction rate for the peeling reaction, as well as for the stopping reaction, of carbohydrates is dependent on the concentration of sodium hydroxide.

The kraft process is a good staging point for observing the pulping reactions of sulfur in an alkali medium. The kraft process exhibits an increase in delignification rate over the soda process as well as reducing the amount of residual lignin at the end of the cook. The theory behind the kraft delignification mechanism is that the hydrasulfide ion activates, and makes functional, certain lignin groups that are otherwise resistant to alkali (9:376). It has been shown that in the presence of the hydrasulfide ion, alkali cleaves the beta-aryl ether structures instead of converting them to enol ether structures (12:247). The hydrasulfide ion is then largely freed from the lignin structures so that the hydrasulfide ion can be said to act as a catalyst in the

process. The catalytic nature of the hydrosulfide ion is evidenced by the fact that there is only a small amount of sulfur present in kraft lignin (9:382).

GL PULPING THEORY

The expected pulping chemistry for a GL cook would have some similarities to the kraft process since it will be an alkaline process and will involve the use of the hydrosulfide ion. However, there should be some major differences. One difference may be the expected reaction rate. Because the concentration of initial effective alkali will be lower in the GL, it follows that the reaction rate for delignification will be slower; therefore, a GL cook will take longer than a kraft cook to reach a constant yield.

Another difference would be that the concentration of alkali should not drop as rapidly in GL cook because of the buffering action of the sodium carbonate. Exactly how this may affect the resulting pulp properties, if it affects them at all, is not clear.

Perhaps the most important difference between a GL and kraft cook is that the ratio of sodium sulfide to effective alkali will be much higher in the GL. One possible effect of this trait may be a more selective cook, thus producing a higher yield. Another possible effect of this higher ratio may be that the residual lignin will not be as resistant to chemical attack as kraft lignin is, thus increasing the bleachablity of the GL pulp. However, through his research activities, Dr. Sarkanon of the University of Washington has

developed a different theory. In his work with green liquor pulping, the details of which he cannot disclose, he found a high amount of condensation type residual lignins. He feels that the initial lignin reactions with green liquor produce large amounts of coniferyl alcohols, which are thought to be lignin condensation precursors. He suggested that a two step green liquor cook would probably produce the best results.

GL PULPING CONDITIONS

The first problem in formulating an experimental plan is deciding on what to base the composition of the liquor. One study on GL semi-chemical pulping used 7.5%TA and 25%S; however, 0.6% of the TA was from NaOH. In this study the pulp was cooked for 24 min. at 180°C with a liquor to wood ratio of 4:1. A Westvaco patent shows that they currently use a continuous green liquor pulping system to produce pulp for corrugating medium. Unfortunately, the exact chemical concentrations, and cooking times are vague. According to the patent, Westvaco uses 5-10g total alkali per 100g O.D. wood, with a range of 24%-48% sulfidity. Westvaco claims the pulping times are in the 20 min. range, but this is with a continuous process. The patent does not state whether the total chemical charge is added at once or in a two step manner, as Dr. Sarkanon mentioned.

EXPERIMENTAL PROCEDURES

PULPING

Liquor solutions were made up using Na_2CO_3 and 60% Na_2S. A total of 12 solutions were made up with each solution being

used for two cooks. The solutions were based on 100 g of O.D. wood and a 4:1 liquor to wood ratio. The chemicals were added to a graduated cylinder along with enough water to bring the total volume to 800 ml. 400 ml of each solution was then used for a cook. Appendix 1. gives the exact make up of each solution. The pulping conditions are given in Table I. The chips and liquor were placed in the bomb digesters and bombs placed in the preheated oil bath, and the cooking time was considered to have started when the temperature again reached setpoint. After cooking, the bombs were quenched in a water bath and the chips removed and washed. Washing of the chips was performed on a 320 mesh screen. The chips were squeezed to remove excess water and weighed. Samples of the chips were then dried to determine their moisture content and the resulting pulping yields. The chips cooked with the same liquor were combined and then passed through the laboratory disk refiner as many times as necessary to defiber the pulps.

REFINING

Refining of the pulps was performed in the PFI mill at 10% consistency with 30 g O.D. fiber. Two final freeness were targeted for each pulp, and two samples were refined for each freeness. In order to refine the pulps to target freenesses it was necessary to stop the PFI mill occasionally and take a 10 g sample to check its freeness. If the sample freeness, corrected only for temperature, was not close enough to the target freeness then the sample was squeeze

Table I. Pulping Conditions

Wood	Trembling Aspen
Chips	
weight	100 g O.D.
avg. size	1 in X 1 in
Liquor:Wood Ratio	4:1
Time to Temp.	20 min
Time at Temp.	35 min
Cooking Temp.	170°C

Table II. Pulp Yields

Liquor #	Total Alkali (%)	Sulfidity (%)	Average Yield (%)
1	10	30	85.54
2	10	20	88.26
3	10	10	92.43
4	7.5	30	87.49
5	7.5	20	89.99
6	7.5	10	93.86
7	5	30	89.21
8	5	20	91.60
9	5	10	95.38
10	10	40	83.86
11	7.5	40	85.81
12	5	40	87.65

Figure 1. Pulp Yield Verses TA at Constant S

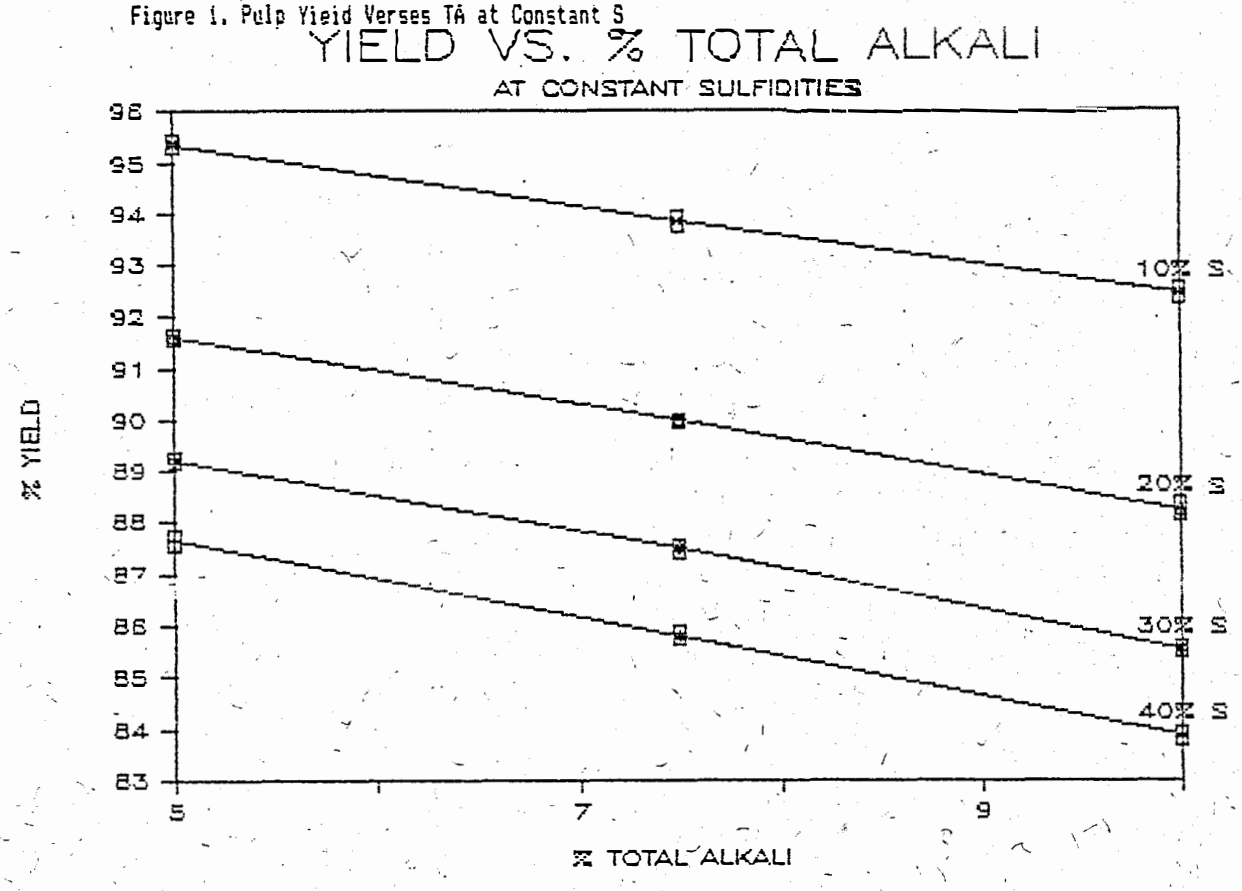
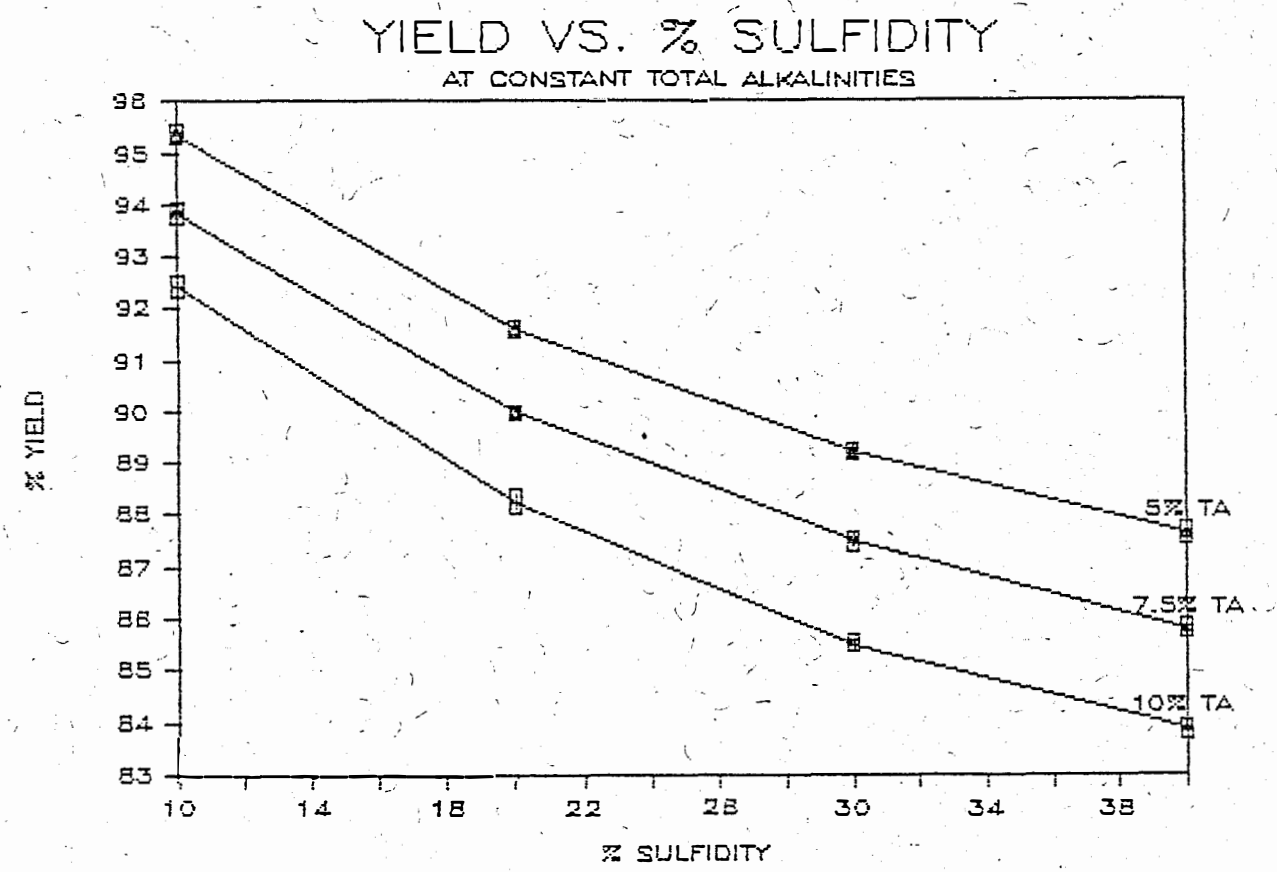


Figure 2. Pulp Yield Versus S at Constant TA



dried back to 10 g and replaced in the PFI mill. The final freeness checks were consistency corrected.

PHYSICAL TESTING

The two samples for each target freeness were combined in the Nobel and Wood proportionator along with enough water to total 10L. One liter from the proportionator was used for each handsheet. The target weight for each sheet was 5.24 g which would be equivalent to the 26#/1000ft^2 used for corrugating medium. The sheets were then allowed to condition for at least 24 hr before testing. The handsheets were tested for basis weight, jumbo mullen (as read), breaking length, and Concora flat crush. Appendix B contains the raw data from these tests.

RESULTS

The pulping results are given in Table II. Table II. shows the average % yield for each liquor condition. The average yield varied from a low of 83.86% with the 10% total alkali and 40% sulfidity liquor to a high of 95.38% with the 5% total alkali and 10% sulfidity liquor. The data from Table I. is illustrated in Figure 1. and Figure 2. Fig. 1. plots the % yields against % total alkali along the four constant sulfidity curves. Fig. 2. plots the % yield against % sulfidity along the three constant total alkali curves.

The results of the handsheet testing may be found in Table III. The testing results are listed along with the % yield of the pulp and the liquor # from which they were produced. Figure 3. shows the relationship between the %

Table III. Physical Testing Results

Liquor #	%TA / %S	Avg. Yield %	Freeness csf	Average Handsheet Weight (lb/1000sf)	Jumbo Mullen psi	Breaking Length km	Concora Flat Crush lbs.
10	10/40	83.855	462	25.9	50.1	4.668	49.3
1	10/30	85.535	453	25.9	45.1	4.119	45.5
2	10/20	88.255	446	26.1	37.3	3.200	35.4
3	10/10	92.43	458	25.9	25.6	1.838	23.6
11	7.5/40	85.805	441	26.1	44.8	4.011	43.3
4	7.5/30	87.49	452	25.8	39.5	3.479	38.3
5	7.5/20	89.985	439	26.0	32.6	2.659	30.6
6	7.5/10	93.86	447	25.9	21.0	1.358	18.4
12	5/40	87.65	450	26.0	39.1	3.492	37.9
7	5/30	89.21	455	26.1	34.9	3.037	33.1
8	5/20	91.595	456	26.2	29.2	1.997	25.3
9	5/10	95.375	440	26.0	16.7	0.799	13.9
10	10/40	83.855	347	26.0	57.5	5.501	61
1	10/30	85.535	356	25.8	52.3	4.895	56.5
2	10/20	88.255	338	25.9	44.0	3.958	47.2
3	10/10	92.43	345	25.9	31.2	2.596	34.8
11	7.5/40	85.805	354	26.1	51.9	4.828	54.4
4	7.5/30	87.49	359	26.0	46.6	4.280	49.9
5	7.5/20	89.985	352	26.1	39.8	3.426	41.7
6	7.5/10	93.86	361	26.0	27.8	2.083	28.1
12	5/40	87.65	343	25.9	46.2	4.292	48.9
7	5/30	89.21	352	26.1	41.9	3.760	45.5
8	5/20	91.595	357	26.0	35.2	3.031	35.9
9	5/10	95.375	348	26.0	22.4	1.640	23.5

Figure 3. Mullen Versus Yield

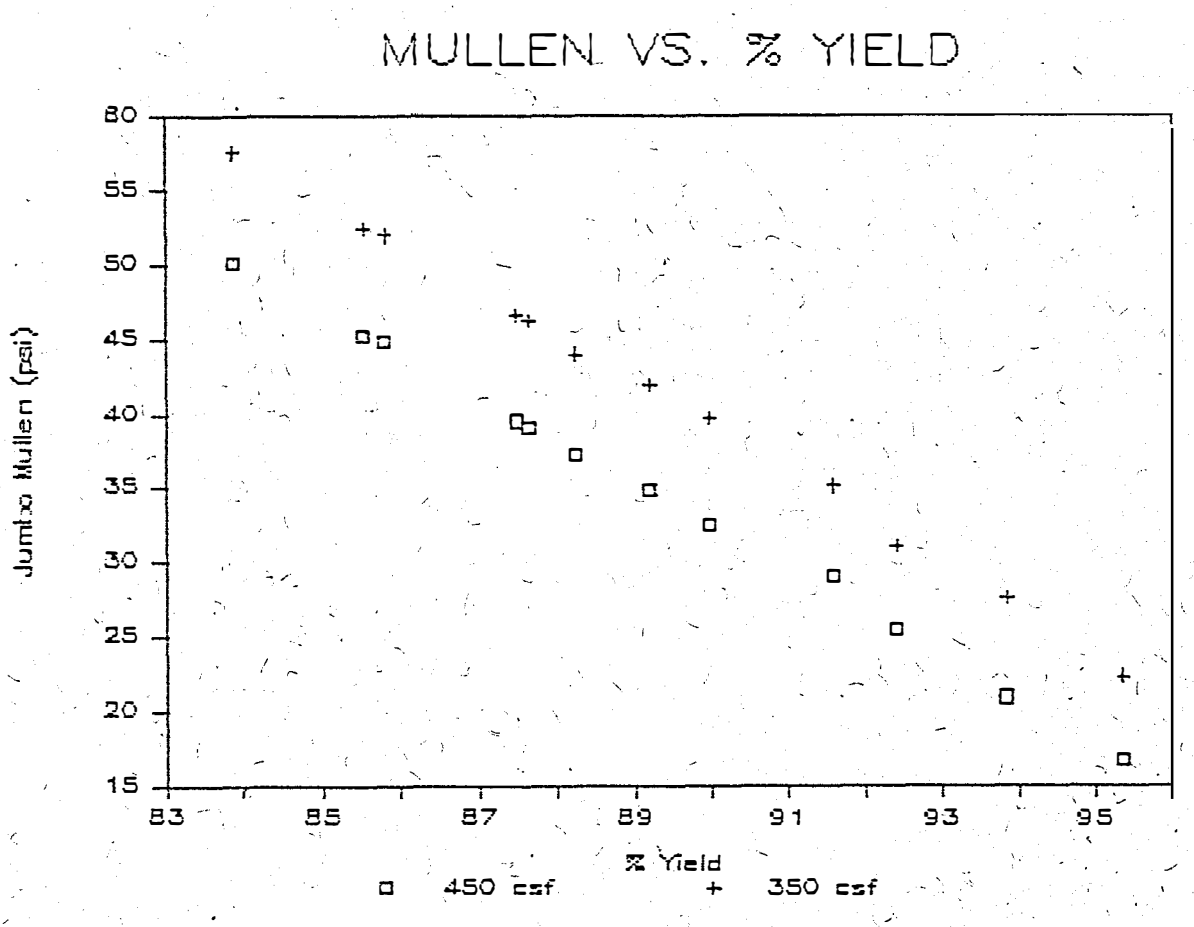


Figure 4. Breaking Length Versus Yield

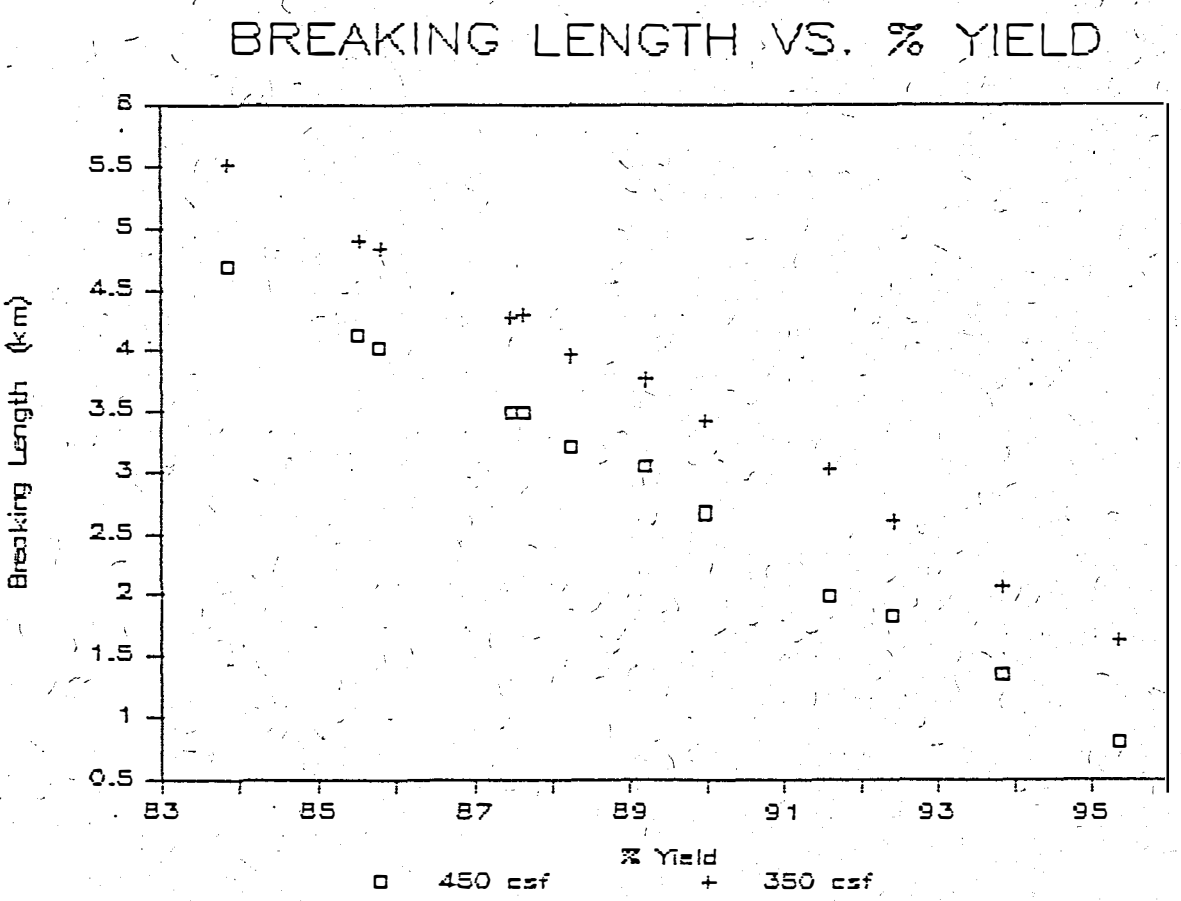
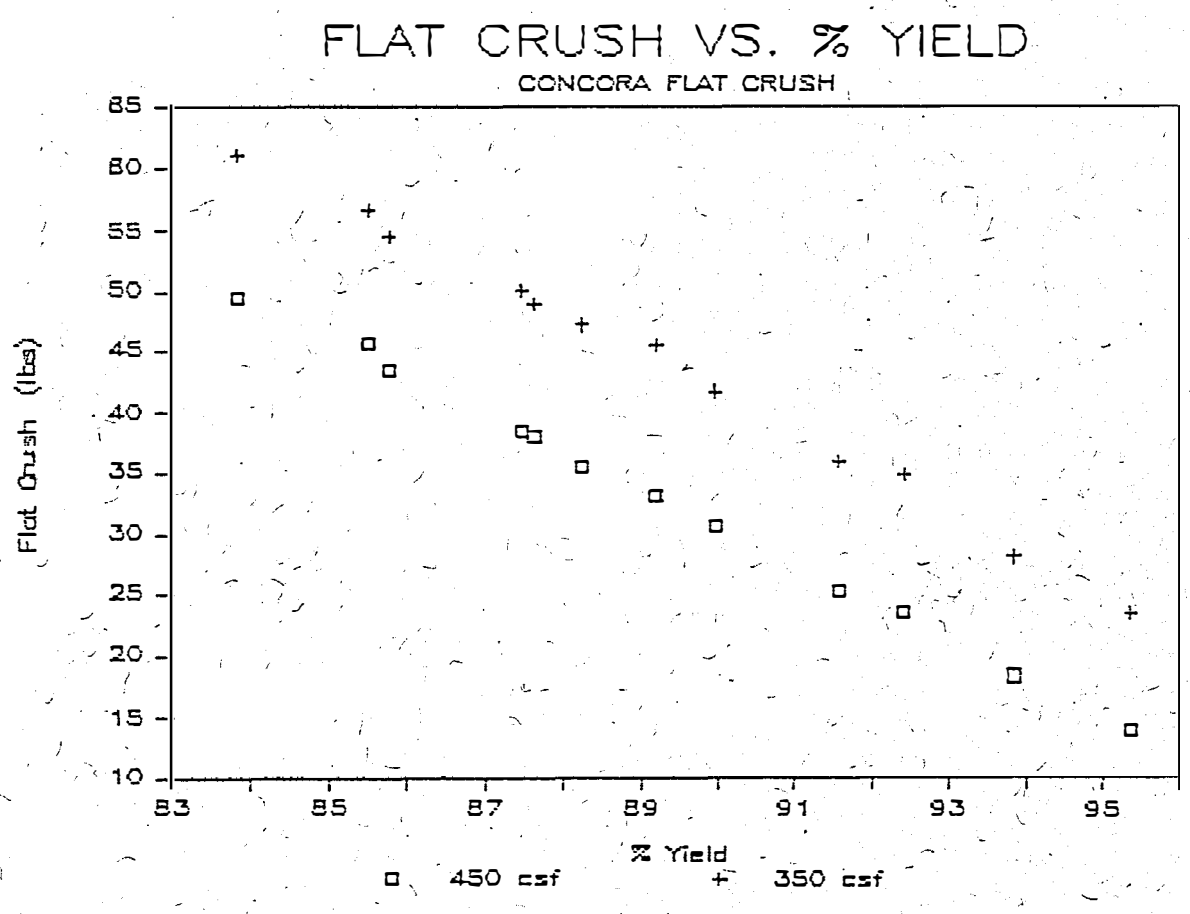


Figure 5. Concora Flat Crush Versus Yield



yield of the pulp and the jumbo mullen of the sheet. Figure 4. illustrates the same relationship between yield and breaking length, and Figure 5. relates yield and Concora flat crush.

DISCUSSION

The yield results from the pulping runs show some good relationships; however, the overall range of yields were lower than expected. The graph in Fig. 1. illustrates two relationships. First, it shows that the relationship between % TA and yield is linear at a given % sulfidity. Second, the graph indicates that at a given %TA the yield decreases, or pulping rate increases, with increasing %S. Fig. 2. clearly indicates a third relationship. The graph shows that while yield does decrease with increasing %S at constant %TA, the relationship is not linear. The graph shows that at a constant % TA, a relatively steep decrease in pulp yield, about 4%, occurs with an increase from 10%S to 20%S. The decrease in yield between 20%S and 30%S drops to about 2.5%, and between 30% and 40% it drops to 1.6%. If equations were fitted to the curves in Fig. 2. it appears that the second derivatives would reach maximums, maximum rate of change, at close to 25%S, indicating that 25%S is the optimum %S for 5%TA, 7.5%TA, and 10%TA. All of the statements made above must be qualified by saying that they are only necessarily valid within the give ranges of %S and %TA, only when pulping under the specified conditions, and only when pulping trembling aspen.

The initial target range for yields was between 70% and 80%; however, the lowest yield was 83.84%. The available literature on green liquor pulping indicated that with the %TA and %S used 25 min at 180°C should have produce yields within the 70%-80% range. The oil bath temperature was set at 180°C; however, the actual measured temperature was 170°C. Since it did not occur to me to check the actual temperature of the bath until halfway through the second pulping run, it was too late to adjust the temperature controller's setpoint. It was decided not to alter the pulping conditions for the remaining two pulping runs. Temperature measurements on the third and fourth runs also showed 170°C at the 180°C setpoint. Another factor that probably affected the yields was the size of the chips that was used. The literature indicated that very small chip sizes should be used to allow rapid liquor penetration. Typical chip sizes were those retained between 5/8" and 3/16" screens with a Williams chip analyzer (3:111). The chips used in these cooks averaged about 1" by 1" since the were meant for an industrial kraft process. Indications are that with a pulping temperature of 180°C and with an average chip size of about 1/2" by 1/2", yields may very well have been in the target range.

The results of the handsheet testing all show the same thing. The strength properties of the pulps are dependent on the yield of the cook with a lower yield resulting in greater strength. The relationship between strength properties and yield appears to be linear on all three graphs. Of course,

these results cannot be assumed to be true when pulping conditions are other than those used here.

CONCLUSION

The results show that, within the pulping conditions given, the strength properties of a green liquor pulp are linearly related to the extent of pulping as given by % yield. It may be concluded that with these pulping conditions the rate of pulping is linear with respect to %TA at a constant %S. The results also show that under these conditions the optimal sulfidity is 25%, and the optimum %TA is dependant only on the desired yield or required strength properties.

RECOMMENDATIONS

The results and conclusions of this project can only be assumed to be valid under the narrowly defined conditions specified. The amount of knowledge about green liquor pulping would be increased if these narrow conditions were expanded. This doesn't mean more variables should be introduced into this experiment, but rather, other variables and relationships should be looked at in the same manner. Some other variables that might be looked at would be the effect of time and temperature on green liquor pulping and the resultant pulps, or one might want to look at the effects of higher total alkalis than those used here. With enough of this type of information it might be possible to create a chart for green liquor pulping that acts as the "H-factor" does for Kraft pulping. Another interesting, and probably

more gratifying, project would be to try green liquor pulping in multiple stages, to prevent lignin condensation, to produce a full chemical pulp. Finally, with the work that has been done on neutral sulfite pulping with anthraquinone, it may be worth while to try anthraquinone in green liquor pulping.

LITERATURE CITED

Becker, E. S., and Caldwell, H.G., "An Evaluation of NSSC and Kraft Pulping of Ecuadorian Hardwoods for Corrugating Medium", TAPPI Journal, TAPPI Press, Atlanta, GA, Vol. 57, No. 12, 1974, p. 117-119.

Bernhard, R., and Backman, K., "The Stora Process for Conversion of Green Liquors from Sulfite Pulping", 1981 Pulping Conference Proceedings, TAPPI Press, Atlanta, GA, 1981, p. 323-329.

Charbonnier, H. Y., et al, "Semichemical Pulping of Pine with Green Liquor", TAPPI Journal, TAPPI Press, Atlanta, GA, Vol. 57, No. 12, 1974, p. 109-112.

Dawson, R. L., "A Comparison of Neutral Sulfite and Green Liquor Semichemical Pulps in Corrugating Medium", TAPPI Journal, TAPPI Press, Atlanta, GA, Vol. 57, No. 12, 1974, p. 113-116.

Hatton, J. V., "The Significance of Residual Effective Alkali/H-factor Relationship in Kraft Pulping Process Control", 1984 Pulping Conference Proceedings, Book 3, TAPPI Press, Atlanta, GA, 1984, p. 469-477.

Hauki, T., and Reilama, I., "The Chemical Cycle and Recovery of Chemicals in NS-AQ Pulping", 1982 Sulfite Pulping Conference Proceedings, TAPPI Press, Atlanta, GA, 1982, p. 41-45.

Kettunen, J., et al, "A Case Study to Convert a Kraft Mill into a NSAQ Mill", 1982 Sulfite Pulping Conference Proceedings, TAPPI Press, Atlanta, GA, 1982, p. 47-53.

Lunden, B., "Stora-Broby Recovery Process for Semichemical Pulp Mills", TAPPI Journal, TAPPI Press, Atlanta, GA, Vol. 53, No. 9, 1970, p. 1726-1731.

MacDonald, Ronald G., "The Pulping of Wood", McGraw-Hill Book Co., New York, NY, 1969.

MacLoed, J. M., "Alkaline Sulfite-Anthraquinone Pulp from Aspen", TAPPI Journal, TAPPI Press, Atlanta, GA, Vol. 69, No. 81, 1986, p. 106-108.

Smook, G. A., "Handbook for Pulp &Paper Technologists", TAPPI Press, Atlanta, GA, 1986.

Tormund, Disa, Teder, & Ants, "New Findings on Sulfide Chemistry in Kraft Pulping", International Symposium on Wood and Pulping Chemistry Proceedings, TAPPI Press, Atlanta, GA, 1989, p. 247-254.

APPENDIX A. PULPING

Liquor Solutions Preparation

Liquor #	Sulfidity (%)	Total Alkali (%)	Total Alkali (g)	Na_2CO_3 as Na_2O (g)	Na_2CO_3 (g)	Na_2S as Na_2O (g)	Na_2S @ 60% (g)
1	30	10.0	20.000	14.000	22.836	6.000	12.580
2	20	10.0	20.000	16.000	27.354	4.000	8.388
3	10	10.0	20.000	18.000	30.774	2.000	4.194
4	30	7.5	15.000	10.500	17.952	4.500	5.536
5	20	7.5	15.000	12.000	20.516	3.000	6.290
6	10	7.5	15.000	13.500	23.080	1.500	3.146
7	30	5.0	10.000	7.000	11.968	3.000	6.290
8	20	5.0	10.000	8.000	13.668	2.000	4.194
9	10	5.0	10.000	9.000	15.288	1.000	2.056
10	40	10.0	20.000	12.000	20.516	8.000	16.774
11	40	7.5	15.000	9.000	15.288	6.000	12.580
12	40	5.0	10.000	6.000	10.258	4.000	8.288

Pulp Yields

Liquor #	%TA / %S	Jar (g)	Jar + Chips (g)	Wet Chip Sample (g)	Dry Chip Sample (g)	Fraction Solids	Yield (%)
1	10/30	398.3	657.5	4.82	1.44	0.2988	85.47
1	10/30	416.9	675.4	4.30	1.29	0.3000	85.60
2	10/20	416.2	668.9	5.00	1.58	0.3160	88.60
2	10/20	415.2	681.6	5.59	1.68	0.3005	88.14
3	10/10	431.9	699.4	5.68	1.78	0.3134	92.53
3	10/10	438.5	691.3	4.11	1.36	0.3309	92.33
4	7.5/30	432.2	717.4	7.85	2.41	0.3070	87.56
4	7.5/30	438.5	723.2	8.63	2.65	0.3071	87.42
5	7.5/20	437.9	727.7	8.66	2.69	0.3106	90.02
5	7.5/20	458.7	757.3	8.83	2.66	0.3012	89.95
6	7.5/10	419.2	728.5	8.61	2.61	0.3031	93.76
6	7.5/10	448.5	757.9	10.57	3.21	0.3037	93.96
7	5/30	46.3	388.1	21.20	5.53	0.2608	89.16
7	5/30	46.3	386.6	18.72	4.91	0.2623	89.26
8	5/20	46.3	400.4	19.67	5.09	0.2588	91.63
8	5/20	46.3	398.8	23.83	6.19	0.2598	91.56
9	5/10	46.3	412.6	20.37	5.30	0.2602	95.31
9	5/10	46.3	413.7	21.52	5.59	0.2598	95.44
10	10/40	46.3	368.1	21.20	5.53	0.2608	83.94
10	10/40	46.3	365.7	18.72	4.91	0.2623	83.77
11	7.5/40	46.3	377.6	19.67	5.09	0.2588	85.53
11	7.5/40	46.3	376.9	23.83	6.19	0.2598	85.88
12	5/40	46.3	383.6	20.37	5.30	0.2602	87.76
12	5/40	46.3	383.3	21.52	5.59	0.2598	87.54

APPENDIX B. PHYSICAL TESTING

Sheet Weights (g) - 450 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	5.22	5.24	5.29	5.20	5.24	5.14	5.25	5.22	5.24	5.22	5.30	5.28
	5.19	5.27	5.20	5.21	5.34	5.26	5.27	5.26	5.23	5.23	5.23	5.24
	5.29	5.23	5.31	5.30	5.26	5.16	5.21	5.24	5.21	5.35	5.37	5.28
	5.20	5.21	5.21	5.29	5.29	5.22	5.23	5.25	5.23	5.24	5.24	5.22
	5.21	5.19	5.27	5.16	5.24	5.26	5.24	5.13	5.27	5.30	5.32	5.22
avg	5.22	5.23	5.25	5.23	5.27	5.21	5.24	5.22	5.24	5.27	5.29	5.25

Sheet Weights (g) - 350 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	5.22	5.15	5.23	5.29	5.22	5.21	5.30	5.26	5.14	5.27	5.24	5.22
	5.27	5.21	5.22	5.22	5.29	5.26	5.26	5.23	5.25	5.26	5.29	5.27
	5.26	5.16	5.20	5.20	5.25	5.28	5.28	5.21	5.21	5.29	5.23	5.27
	5.26	5.24	5.18	5.30	5.29	5.26	5.23	5.28	5.24	5.23	5.21	5.26
	5.24	5.27	5.25	5.13	5.26	5.26	5.25	5.28	5.25	5.30	5.26	5.25
avg	5.25	5.21	5.22	5.23	5.26	5.25	5.26	5.25	5.22	5.27	5.24	5.25

APPENDIX B. PHYSICAL TESTING

Jumbo Mullen (psi) - 450 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	50.9	45.1	37.9	25.9	44.5	39.5	32.3	20.5	39.5	35.5	28.7	17.1
	51.7	46.0	37.5	25.8	44.6	39.8	31.8	20.9	39.2	35.5	29.9	16.2
	49.8	44.1	37.5	25.5	45.5	39.4	32.5	21.3	39.9	35.5	28.3	17.6
	50.0	45.5	37.0	25.9	44.8	40.7	33.8	21.4	39.0	34.8	28.6	16.1
	50.0	44.6	37.1	24.7	44.5	39.7	32.6	21.1	39.0	34.4	28.8	17.0
	48.6	44.3	36.9	25.0	43.0	39.0	32.1	21.9	38.2	34.2	29.0	16.1
	50.1	45.7	36.1	26.3	44.9	40.4	32.9	20.4	39.5	35.8	29.6	16.8
	50.6	45.6	37.9	25.0	44.4	39.3	33.4	21.3	39.8	35.3	29.5	17.0
	49.2	46.0	37.9	26.7	45.6	39.1	32.1	20.8	38.9	34.1	30.0	16.2
	49.9	44.2	37.2	25.5	45.8	38.5	32.6	20.2	38.2	34.3	29.2	17.2
average	50.1	45.1	37.3	25.6	44.8	39.5	32.6	21.0	39.1	34.9	29.2	16.7
std dev	0.671	0.713	0.639	0.688	0.758	0.618	0.584	0.496	0.560	0.615	0.546	0.512

Jumbo Mullen (psi) - 350 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	57.1	51.4	44.7	30.9	52.8	46.5	40.6	28.3	46.4	42.5	35.5	22.2
	57.0	52.5	43.7	31.9	51.9	45.2	39.3	27.4	45.7	42.1	35.9	22.1
	57.5	52.1	44.4	30.6	51.1	45.6	39.7	28.2	45.6	42.0	34.8	22.8
	57.1	53.2	43.7	30.1	53.7	46.5	40.4	28.8	46.7	41.1	35.9	23.0
	58.7	51.7	43.7	31.7	52.9	46.7	39.3	27.9	46.2	42.2	34.5	22.0
	57.2	52.7	44.8	30.8	51.5	46.7	39.7	26.4	46.6	42.0	34.1	22.0
	57.7	52.2	42.6	32.7	51.0	47.9	40.0	27.9	46.9	41.9	34.4	23.3
	56.2	53.3	44.7	31.6	52.1	46.8	40.9	28.4	45.7	41.4	35.6	22.2
	57.9	51.1	44.6	30.9	51.1	46.6	39.7	27.8	45.1	43.0	35.8	22.2
	58.6	52.4	43.5	31.1	51.0	47.0	38.8	27.1	46.9	41.1	35.0	22.6
average	57.5	52.3	44.0	31.2	51.9	46.6	39.8	27.8	46.2	41.9	35.2	22.4
std dev	0.721	0.683	0.679	0.711	0.903	0.697	0.614	0.663	0.591	0.569	0.641	0.434

APPENDIX B. PHYSICAL TESTING

Tensile (kg/15mm) - 450 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	8.80	8.02	6.12	3.37	7.75	6.56	5.08	2.52	6.52	5.79	3.88	1.56
	9.00	8.11	6.20	3.47	7.47	6.62	4.99	2.52	6.50	5.84	4.01	1.45
	8.77	7.92	6.13	3.48	7.83	6.52	5.21	2.55	6.85	5.83	3.66	1.56
	8.91	8.00	5.94	3.30	7.78	6.73	4.98	2.65	6.56	5.86	3.80	1.41
	8.62	7.87	6.25	3.59	7.62	6.69	4.99	2.58	6.75	5.83	3.73	1.43
	8.89	7.82	6.02	3.36	7.51	6.52	4.96	2.64	6.65	5.91	3.88	1.67
	8.73	8.08	5.96	3.43	7.55	6.61	5.13	2.53	6.51	5.81	3.97	1.63
	8.96	7.83	6.14	3.64	7.68	6.72	5.29	2.63	6.68	5.56	3.74	1.44
	8.96	7.94	6.25	3.77	7.73	6.56	5.04	2.49	6.77	5.77	3.77	1.51
	8.89	8.04	6.16	3.46	7.75	6.72	4.95	2.64	6.70	5.84	3.87	1.55
average	8.85	7.96	6.12	3.49	7.67	6.63	5.06	2.58	6.65	5.81	3.83	1.52
std dev	0.114	0.095	0.106	0.135	0.116	0.081	0.107	0.057	0.118	0.088	0.104	0.084

Tensile (kg/15mm) - 350 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	10.75	9.18	7.44	4.92	9.36	8.03	6.50	3.99	8.07	7.13	5.66	3.07
	10.57	9.12	7.48	4.81	9.33	8.09	6.51	3.85	8.06	7.12	5.71	3.20
	10.42	9.45	7.70	4.99	9.09	8.13	6.64	4.18	8.33	7.10	5.78	3.16
	10.40	9.43	7.73	5.02	9.04	8.18	6.57	4.12	8.25	7.14	5.82	3.11
	10.56	9.16	7.43	4.78	9.35	8.36	6.66	3.99	8.10	7.15	5.76	2.97
	10.56	9.24	7.57	4.75	9.28	8.27	6.54	3.92	8.06	7.09	5.89	3.01
	10.40	9.32	7.38	5.07	9.21	8.04	6.48	3.85	8.27	7.36	5.85	3.13
	10.26	9.32	7.33	5.06	9.36	8.01	6.31	3.96	8.26	7.37	5.92	3.22
	10.49	9.20	7.57	4.92	9.14	8.19	6.62	3.87	8.00	7.15	5.86	3.16
	10.32	9.07	7.43	4.92	9.14	8.20	6.66	3.92	8.03	7.26	5.93	3.20
average	10.47	9.25	7.51	4.92	9.23	8.15	6.55	3.97	8.14	7.19	5.82	3.12
std dev	0.135	0.121	0.126	0.107	0.115	0.108	0.101	0.104	0.115	0.099	0.085	0.078

APPENDIX B. PHYSICAL TESTING

Concora Flat Crush (lbs.) - 450 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	49.2	46.4	35.2	23.6	44.9	38.2	30.4	17.3	37.7	32.9	25.7	14.2
	49.7	46.8	36.6	23.2	43.4	39.2	30.2	18.7	37.0	32.1	25.6	14.5
	50.4	45.9	35.5	24.9	43.2	38.2	31.8	18.3	38.5	34.0	24.4	13.6
	50.3	45.4	35.7	24.3	43.6	38.1	31.2	19.0	38.9	33.4	24.2	13.4
	48.7	45.4	35.7	23.2	42.1	38.9	30.7	18.2	37.3	32.2	25.4	13.3
	48.2	45.5	34.9	23.1	42.9	38.3	30.6	18.4	38.0	32.5	25.4	13.7
	49.4	44.4	35.8	23.6	43.3	37.2	30.9	18.7	37.3	33.3	25.9	14.6
	49.8	44.3	35.6	23.0	42.5	37.3	30.2	18.3	37.6	33.5	25.6	14.3
	48.7	45.4	34.0	23.4	43.8	38.8	29.7	18.3	38.5	33.4	25.5	13.6
	48.5	45.4	34.5	23.5	43.4	38.4	30.3	18.7	38.4	33.7	25.2	13.4
avg	49.3	45.5	35.4	23.6	43.3	38.3	30.6	18.4	37.9	33.1	25.3	13.9
std	0.722	0.731	0.697	0.562	0.719	0.607	0.562	0.437	0.603	0.613	0.528	0.465

Concora Flat Crush (lbs.) - 350 csf

	10/40	10/30	10/20	10/10	7.5/40	7.5/30	7.5/20	7.5/10	5/40	5/30	5/20	5/10
	61.2	57.6	47.9	34.2	54.1	49.1	41.4	28.7	50.0	45.9	35.5	22.6
	60.2	57.7	48.6	34.7	54.1	49.3	41.6	27.4	49.7	45.7	35.2	23.2
	61.2	57.0	47.5	35.0	54.1	50.8	41.2	28.6	48.3	44.0	36.8	23.5
	61.5	56.2	47.4	34.6	54.5	50.5	41.4	29.0	48.4	45.2	35.9	23.6
	61.7	56.2	46.8	36.0	55.7	49.0	41.1	27.9	48.7	45.6	36.5	23.4
	61.9	56.4	46.4	35.7	55.6	49.7	41.3	27.3	48.5	46.0	36.1	23.4
	59.4	55.4	47.3	34.1	54.4	50.7	41.9	27.9	49.9	45.0	36.4	23.4
	60.3	55.7	47.5	34.6	54.1	50.9	41.7	28.4	49.5	45.3	35.6	23.5
	61.1	56.1	46.5	34.3	53.6	49.9	43.1	28.0	48.0	46.7	35.8	23.9
	61.9	56.8	46.3	34.8	53.4	49.4	42.6	27.6	48.4	45.8	34.8	24.3
avg	61.0	56.5	47.2	34.8	54.4	49.9	41.7	28.1	48.9	45.5	35.9	23.5
std	0.783	0.720	0.691	0.590	0.716	0.700	0.613	0.546	0.712	0.679	0.583	0.417