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THE EFFECT OF A VIBRATING SERRATED SLICE AND THE SUBSEQUENT PAPER FORMATION

By
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A thesis submitted
in partial fulfillment
of the requirements for the
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INTRODUCTION

Paper exhibits a wide range of physical and optical properties, all, in essence, can be said to depend on one property, its internal structure, more commonly known as its formation. Generally, the sheet structure is largely determined by the orientation and distribution of the fibers in the finished sheet, both across the sheet and through its thickness. Paper is like most other materials, it is only as strong as its weakest link. Because paper is a complex, heterogeneous material, it is extremely sensitive to the weak link concept.

Higher headbox consistencies are being used by the industry to reduce overall water handling in the paper making process. High consistencies create problems with paper formation, pushing the use of various devices to improve the drainage, orientated shear and turbulence to the pulp on the wire. As a result, improvements in formation properties, as well as fiber orientation, can be expected. Slower machines are often equipped with a shake mechanism, which improves sheet formation, but has little effect on the fiber orientation. As the machines get faster, the shake effects decrease, due to the nearly instant setting of the pulp suspension. A stationary serrated slice mechanism, designed for the faster papermachines, causes stock ridges and valleys to occur in a controlled manner as the pulp suspension leaves the headbox. Collapsing of the stock ridges and valleys occur as water is pulled from the web by gravitation and suction forces from drainage elements. Phase changes cause ridges to form valleys and valleys to form ridges. Several phase changes occur as the pulp suspension travels down the machine, until a full collapse results. The collapsing action creates a shear and turbulence to the pulp suspension resulting in improved sheet formation and fiber orientation along the direction of the collapsed ridges. Vibrating the serrated slice mechanism causes the stock ridges and valleys to oscillate back and forth down the length of the machine. The intent of this thesis is to examine the effects the vibrating serrated slice has on paper formation and fiber orientation at above normal headbox consistencies.

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LITERATURE SURVEY

The formation of paper has always been a problem for papermakers due to its nonuniformity within the sheet. The key variables affecting formation are found in the headbox. The basic function of the headbox is to spread dilute stock evenly across the width of the wire uniformly dispersed at a steady rate with minimum possible disturbances. When stock is badly flocculated and improperly delivered onto the wire, the chances are good that formation will be poor.

Locke$_2$ lists five main controllable variables of the headbox that are important to formation:

1. The slice geometry
2. The headbox consistency
3. The jet to wire speed ratio
4. The rectifier roll, speed, position and design
5. The headbox liquid level

The Headbox Slice

The headbox slice is a full width orifice or nozzle with an adjusted opening to give the desired flow rate. The slice geometry and opening determine the thickness of the slice jet, while the pressure within the headbox determines the jet velocity.

The slice has a top and bottom lip. The top lip is adjustable up or down as a unit, as well as in local areas, by use of individual adjusters. Both the top and bottom lips are adjustable in the horizontal direction to change the impingement angle of stock jet onto the forming wire. Both the point of impingement and the impingement angle onto the wire are important for achieving satisfactory formation and drainage on the forming wire.

The Headbox Consistency

The consistency of the stock in the headbox is also important from the standpoint of fiber flocculation. The degree of flocculation that will occur is dependent upon the physical nature of the furnish, as well as how much of the furnish is present in the pulp suspension. The consistency is normally kept as high as possible to reduce the handling of large volumes of whitewater. On the other hand, as consistency goes up, flocculation time goes down rapidly. The closer the fibers are, the more quickly they will start to form flocs. Another factor that influences flocculation time is the length of the fiber. The longer fibers sweep out more volume in their motion and thus will have a greater opportunity to collide with another fiber and begin to form flocs. Due to the dependency of fiber flocculation on consistency and the impracticality of using too low of a consistency, most paper today is made between 0.1% and 1.0% consistency.

The Jet to Wire Speed Ratio

This ratio between the stock velocity leaving the headbox to the speed of the wire is important for controlling formation properties of the paper. If the stock velocity is slower then the wire velocity, fibers are caught by the wire and will line up in the machine direction. If the stock velocity is greater then the wire velocity, fibers will tumble over one another creating a wave down the machine. Therefore, the ratio is usually adjusted near unity to achieve the best formation. This ratio can be adjusted to improve drainage or change the fiber orientation.

The Rectifier Roll, Rpeed, Position and Design

Rectifier rolls are mounted within the headbox and are commonly used to dampen flow irregularities and to create turbulence to keep fibers deflocculated. The major design and operation variables of the rectifier roll are its hole diameter, % open area, wall thickness, direction of rotation and rotational speed. Typically, two to five rectifier rolls are installed to reduce the potential of stock bypassing the rolls.

The Headbox Liquid Level

Headbox liquid level was used on earlier paper machines to control the jet velocity. With increasing paper machine speeds, headboxes were closed off, making jet velocity a function of the feeding pump pressure and the air within the headbox. This step in technology has made the headbox liquid level an indirect variable to formation.

Orientation

If paper was made by sheet mold process, paper formation and fiber orientation would not be an issue. For obvious reasons, paper is manufactured as a continuous process that involves movement between the forming mat and the wire. This movement pulls fibers in the machine direction, thus producing a sheet with a greater number of fibers aligned in the this direction, rather than the cross direction. This orientation gives the sheet higher strength in the machine direction and lower strength in the cross direction. If fibers were orientated equally in both MD and CD direction, the sheet would have similar strengths in both directions. When this occurs, the sheet is described as having a degree of sheet squareness.

Methods of Improving Formation and Orientation

Adjusting the major headbox variables affecting the stock delivery system, tends to distort, rupture and disintegrate the flocs, but even at the highest shear rates, fiber dispersion is not complete at the higher headbox consistencies. As a result, fiber interaction and entanglement are still evident. According to Joe Parker[4], the minimum number of fibers required to form a floc with distinct mechanical properties is four. Flocs with four fibers can form and then increase to large amounts. As the floc gets larger and larger, it begins to take on the properties of a network containing smaller flocs linked together. This process is a result of what occurs during the forming process as water is removed from the forming sheet. At first, these networks are loosely formed. As water is removed, the networks become more and more rigid. As a result, the energy required to rearrange the fiber distribution within the network becomes greater and greater. Ultimately, the only way to rearrange the network is to rupture it and the sheet would be destroyed. Between the headbox and the point where the sheet can no longer be changed (dryline), the opportunity exists to influence the formation and structure of the sheet. By applying a degree of agitation to the pulp suspension between the headbox and the dryline on the wire, fiber flocs can be destroyed or kept from floccing prematurely, therefore, causing the poor sheet formation. It must be pointed out that shear and turbulence on the wire cannot replace a good dispersed delivery from the slice. However, good delivery alone can be adversely affected by an inactive wire section.

Shake

The shake on the machine imparts a cross oscillation motion in the cross machine direction to the web birthing area of the wire. This work is done to reduce the tendency of fibers to flocculate, which can occur within milliseconds in the absence of the shear and turbulence. This shake mechanism of the wire requires large driving forces that will create mechanical wear over time. The effect the shake has on the pulp suspension carried by the wire is minimal, unless it's running at uneconomically low speeds (400 m/min.).

Sheraton Roll

The Sheraton roll is similar to the table roll, but there is an added sawtooth pattern designed along its surface. It is used underneath the wire between the headbox and dryline to introduce turbulence to the pulp suspension. This device has been extremely successful if driven at a speed that generates the resonant frequency of the length of the free wire above the roll$_3$.

Serrated Slice

A practical idea was experimented with that involved machining a sine wave pattern in the top lip of the slice. This design would generate ridges in the slice flow, which would subsequently split as they went over drainage elements on the wire. The splitting action is caused by gravitation and downward suction forces at the drainage elements. When two adjacent ridges meet, they form a ridge where there was once a valley. This action is known as a phase shift (see Figure 1). After each phase shift, the ridges reduce in size to about half their original size. After several phase shifts, the ridges become so small that no more phase shifting can take place. The hydraulic shear created in this application helps break flocs and keep the fibers dispersed. The generation of these ridges should be carefully controlled. If they are too large, they will be disruptive to sheet formation when they divide and cause spouting on the wire. This application could be quite beneficial to formation, if the ridges were of correct size, spacing, and energy level and the phase shifting was properly done$_6$. The apparent mechanism is intended for the shear forces to pull the flocs apart and redistribute the fibers. The phase shifts collapse the formed ridges in the opposite direction of the slice flow. This redistribution affect tends to orientate fibers in the cross machine direction

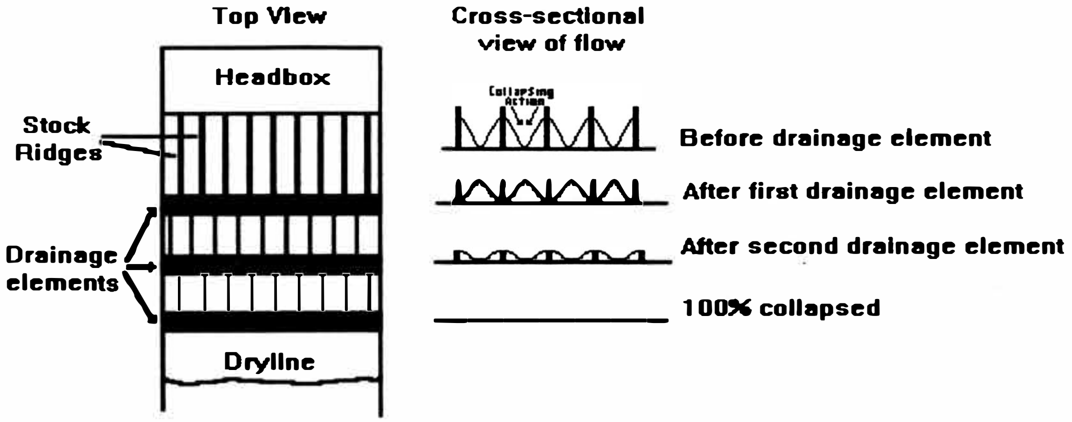


Figure 1. Effect of drainage elements on the phase change

The amplitude and period of the machined sine wave into the upper lip of the slice depends on the slice opening. As the slice opening increases, the amplitude and period must increase. The greater number of ridges created in the stock during the forming process, the better the formation of the resulting sheet.

Spacing of the suction boxes is very important in optimizing the serrated slice effects. Placing them at the proper distance apart will give the desired splitting action of the ridges needed as the sheet thickens.

Effect of Sheet Formation on Tensile Strength

Tensile strength is determined by measuring the force required to break a narrow strip of paper. The tensile strength properties of paper are dependent upon the combined effect of several factors. According to Britt[8], they are:

1. The individual strength of the fiber
2. The average length of the fiber
3. The bonding ability of the fiber surface
4. The structure and formation of the sheet

Of the listed factors, the effect structure and formation of the sheet is the primary concern of this study. As mentioned earlier, paper is only as strong as its weakest link. Poor formation can generally be described as random areas of high and low fiber concentrations throughout the sheet. Areas in the sheet with higher fiber concentrations will to have a greater ability to withstand the tensile loads than the lower fiber concentration areas. As a result, tensile failure will occur at these low concentration areas i.e. the weakest link.

Fiber Orientation Effect on Formation

The standard tensile strength is based on a large testing specimen. This testing specimen could possibly contain many high and low fiber concentration areas. If the testing specimen was significantly reduced, the tensile strength would be a test of the individual fiber strength. The results from this test would be dependent only on the amount of fibers present in the test, assuming that all the fibers in the paper have similar strengths. A test to determine the individual fiber strength, while taking into account the high and low fiber concentration areas of the test specimen is done using a zero-span tensile tester.

The results from the zero-span tensile tester cannot be accurate without taking into account the affects that fiber bonding and curl has on the results[9]. An easy way to minimize these effects is to take the ratio between the machine and cross direction zero-span tensile strengths. The only variations then remaining from the ratios will be a result of the number of fibers in the test. The number of fibers involved in the test will be determined by the degree of fiber orientation of the sheets.

STATEMENT OF THESIS

Increasing paper production while reducing material and energy usage is constantly being studied in the paper industry. The literature search in this study suggests several ways to optimize machine variables in order to improve formation properties. However, the literature did not mention a way to optimize formation machine variables in terms of reducing material and energy usage.

If higher headbox consistencies could be used, while preserving formation properties in the finished sheet, tremendous water handling could be reduced. The main objective of this study is to produce paper at above normal headbox consistencies with similar formation properties of paper produced at the normal headbox consistencies. This objective was to be achieved using a specially designed vibrating serrated slice on the Western Michigan Pilot Plant paper machine. Determination of comparable formation properties will be based on test results from tensile index, zero span tensile, opacity deviation and formation index values.

EXPERIMENTAL DESIGN

Vibrating Serrated Slice

The specially designed vibrating serrated slice was constructed to oscillate the formed ridges and valleys created by the serrated edge. Theoretically, the collapse of these ridges will create high intensity fine scale turbulence to the pulp suspension. These turbulents will redistribute fiber flocs, enhancing the sheet squareness and formation in the resulting sheet.

The vibrating serrated slice mechanism was constructed by fastening a serrated surface made of acrylic plastic to a frictionless track. The frictionless track was driven by an electric power drill. The drills rotational motion was converted into an oscillating motion through a cam and pendulum system.

The track design (see Figure 2) consisted of two wood boards the length of the width of the paper machine. The two boards were dadoed in a way in which one acted as a support for a ball bearing track for the other one to ride in.

The serrated surface was cut into the acrylic plastic using a rod bit cutter of a duplicator machine. The rough edges were sanded and then smoothed using a flame from a cigarette lighter. The serrated edge pattern was generated by a personal computer, plotting the mathematical cosine function at the desired amplitude and period. The cut represents a sinusoidal wave which best fits the natural shape of fluid flow. The period and amplitude were chosen to be 0.75 and 0.375 of an inch respectively. The period and amplitude values were designed to produce a period/amplitude ratio of two, therefore producing 45 degree surface angles in the pulp suspension. This angle will yield the greatest potential energy to be used in creating the necessary shear and turbulence without entraining air in the pulp suspension.

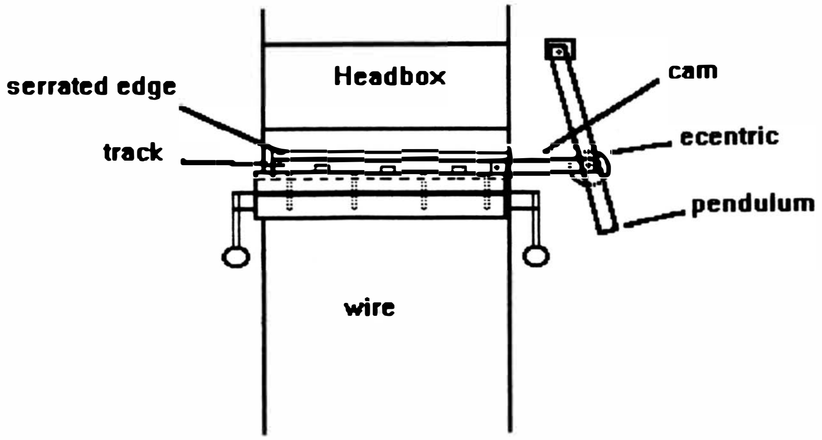


Figure 2. Vibrating slice mechanism

The overall dimension of the slice was designed to effect the center 22 inches in the cross machine direction with a 0.25 inch clearance above the wire. To eliminate many problems associated with initial formation of the sheet, the serrated slice was positioned 4 inches down the machine. This position created a fiber dispersing stock rectification zone prior to the beginning of sheet formation.

The track was driven using a half horsepower/1000 rpm electric drill motor. The electric drill motor was connected through a rheostat to control the voltage gain of the electric drill, so selected frequencies could be obtained. The drills rotation output was converted into oscillation output using an eccentric to drive a cam and pendulum system. The eccentric was made using a metal dowel rod fastened to a metal disk. Another metal dowel rod was placed in the metal disk at a distance equal to half the desired amplitude of the oscillation motion from the center of the disk. This metal dowel rod was connected to the cam of the system. A pendulum arm connected the cam to the track. The connection point on the cam was designed to move up and down its length, so easy adjustments could be made to the amplitude of the slice. The other end of the cam was fastened to a stationary pivot point to provide the arc for oscillation motion.

Slice Frequency

Low, medium and high slice frequencies were arbitrarily chosen ,with careful attention not to exceed 50% of the machine speed. Slice frequencies of less than 50% of the machine speed will form ridges in the pulp suspension that will not exceed 45 degrees angles off the slice edge peaks (seen in figure 3). Ridges at greater angles will retard the machine direction speed, therefore reducing the potential area of disturbance to the pulp suspension. Using a predicted machine speed of 70 ft/min., frequencies were calculated (Appendix IV) to be 180, 300 and 480 cycle/min.

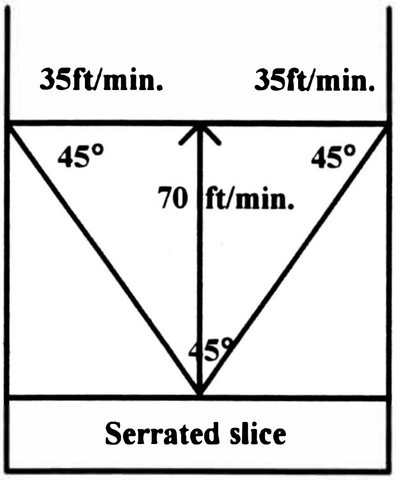


Figure 3. Frequency design

To verify the objectives, a series of machine trials were set up using 121 conditions shown in Appendix I. Runs 1-18b were designed to determine the effect on formation and fiber orientation of increasing serrated slice frequency at high, medium and low consistencies. In an attempt to optimize the results in runs 1-18b, the slice opening was varied between 1.5 and 1.25 inches. The purpose of run 6b, 12b and 18b was to establish a base line for normal operation at the high, medium and low consistency respectively, on the machine.

For each machine run, consistency and paper samples were collected, conditioned and tested. Each sample was tested for MD and CD tensile index, MD and CD zero span index, opacity deviations and formation index.

EXPERIMENTAL PROCEDURE

Preliminary

Pictures of the wet end of the machine were taken prior to construction of the cam and pendulum system to aid in its design.

Observations and paper samples were conducted on the pilot plant fourdrinier using three serrated edges of different geometries. Tensile ratios were tested on the samples. The results from the test, along with the observations, aided in the final design modifications and slice geometry.

The basis weight profile was found to be easily adjusted if the serrated edge was fastened to the adjustable dam.

Machine Runs

First, the furnished blend of 50% bleached softwood, 50% bleached hardwood was pulped. A freeness of 450 CFS with no fillers or additives was targeted for the final furnish.

While the furnish was being prepped, there was time to assemble and fasten the vibrating serrated slice mechanism to the paper machine. The track was clamped to the dam which is normally used in creating a secondary head. This dam was equipped with finger screws that adjusted the height of the front and back above the pulp suspension. This adjusting dam was used in the runs to balance the basis weight profile of the web. The cam and pendulum and motor assembly were then clamped to machine supports. The drive motor was plugged in, and three rheostat positions were tested to make sure the drive system was sound at all three frequencies.

Next, consistency sampling buckets were marked and placed in a convenient location for later sampling of each of the runs.

Once the machine conditions were met and the machine settled down, sampling began. During each run, a paper and consistency sample were taken, then labeled and stored. The basis weight, machine speed, stock flow and dryline location were all recorded. Observations were also made of the pulp suspension exiting the serrated slice.

Testing

Once the final run was completed, the paper samples were brought to the paper testing lab where they were cut down to a manageable size. The samples were then stored under standard conditions for at least 24 hours. The consistency samples were tested.

The nonconstructive tests were performed first. Five 8.5 inch x 11 inch samples were cut and placed in a plastic bag. These samples were tested at Simpson Paper Company on a M/K Microformation tester.

Ten 6 inch diameter circles were cut and weighed for basis weight according to TAPPI Standards T410.

Fifteen opacity readings were completed for each run in the same direction according to TAPPI Standards T425. Opacity deviations were examined as a indication of formation quality.

Ten samples for each run were tested for burst according to TAPPI Standards T403. Burst indices were calculated to eliminate the effect of basis weight variations. Similar to the opacity test, deviation in burst was examined as an indication of formation quality.

Ten MD and CD tensile samples were completed for each run according to TAPPI Standards T494. Tensile indices were calculated to eliminate the influence of basis weight on the tensile load.

Ten MD and CD zero span tensile samples were completed for each run according to TAPPI Standards T231. A ratio was then calculated using the MD and CD tensile values obtained.

RESULTS AND DISCUSSION

The machine runs 1-18b discussed in the experimental design and listed in Appendix I, were completed to some success. Runs 19 through 24 were unscheduled runs performed to put good use to the remaining stock. Run 25 was a repeat of run 18b. Runs 19 and 20 can be used to show the effect of a stationary serrated slice on formation and fiber orientation paper properties. The shake was to be applied to runs 19 and 20 to get runs 21 and 22. These runs can be used to observe the effects of both the oscillating wire and oscillating serrated slice. The stationary serrated slice was removed from runs 21 and 22 to get runs 23 and 24. These runs can be used to determine the effects of the shake device acting alone on formation and fiber orientation paper properties.

The specially designed vibrating serrated slice, with the aid of some silicon spray, held up remarkably well and was able to produce the desired frequencies with few problems. A well defined criss-cross pattern was seen on the surface of the pulp suspension of the vibrating serrated slice runs. The dryline in the serrated slice runs appeared to approach the head box as the slice frequency was increased.

The general objective of the multiple machine runs was not to optimize the affects of the serrated slice, but to conduct enough machine variations to get positive data that would best represent the desired outcome.

Consistency and paper samples were taken for each of the 25 machine runs. The paper sample for the control runs at high and medium consistency (6b and 12b) were not taken

As can be seen in Appendix I, the actual consistencies were much lower than the desired target. Although the target consistencies were not meant, a low and medium level of consistency for the vibrating serrated slice runs still exist. This presents a problem with the initial objective to examine the effects of the serrated slice at above normal headbox consistencies. With the high consistency at only 0.6% and the low at 0.4%, it leaves a 0.2% difference between the high and low levels of consistencies. However, this difference, especially on industrial size processes, is a significant amount. As seen in Appendix III, the amount of water required to dilute the 0.6% to 0.4% consistency for this machine trial is 2,200 gallons. Therefore, observing the affects at both high and low consistency could give some indications to what happens as the consistencies in the headbox is increased. The objective can be better described as a study to determine the effects of the vibrating serrated slice on formation and fiber orientation properties at two levels of head box consistency.

After analyzing the results from the paper tests listed in the experimental design, seven runs were selected to best represent the objective. Three of the unscheduled runs were selected for further analyzing. These runs were highlighted in Appendix I and were reorganized for the final analyzing seen in Appendix II

Throughout the 10 machine runs, stock flow was constant with respect to the level of consistency used. As mentioned in the experimental procedure, all machine variables, with exception of consistency and device, were held constant. As a result, within the respective level of consistency, the mean basis weight should also remain constant. However, as the frequency of the serrated slice increased for both the normal and high consistencies, the mean basis weight decreased (seen in Figure 4). For practical purposes, the slight decrease in stock flow at the highest slice frequency of both consistencies is not of enough significant magnitude to support these drops in mean basis weight (seen in Figure 5).

One speculation is that there may be a correlation between increasing slice frequency and the level of penetration of shear and turbulent forces to the pulp suspension. If shear and turbulence forces penetrated further into the pulp suspension, disruption of the filtration mechanism of the sheet forming process may occur. This disruption may cause fiber in the filtered fiber mat to rotate with the prefiltered suspension. This rotation could initially allow some of the fines and shorter fibers to slip through the wire. Then, as the pulp was carried further down the machine, the turbulent forces would decrease at the wire level, resulting in a new beginning of the filtration process.

If this were true at the higher frequency, then the lower frequency should have shallower penetration, therefore, not totally disrupting the filtration mat at the wire level. As a result, the lower frequency should have better overall retention. The shallower penetration may also create the rotational motion as described at the high frequency. In this case, only the top few layers of the filtered fiber mat are circulated with the prefiltered suspension, causing an immobilization effect. When fibers in suspension are immobilized by the fiber mat, they floc together in coherent networks: drainage then occurs by thickening and a more felted floccy sheet exists[3].

If the previous speculation are true, than the mean basis weight should decrease and formation index should increase at both consistencies as slice frequency is increased. These results are seen in Figure 6 with the higher of the two consistencies being slightly affected more. For practical purposes, formation index values are said to be comparable within basis weight ranges of plus or minus 20%. The resulting variation in the basis weights are within these tolerances.

Figure 4. Basis Weight Vs. Runs

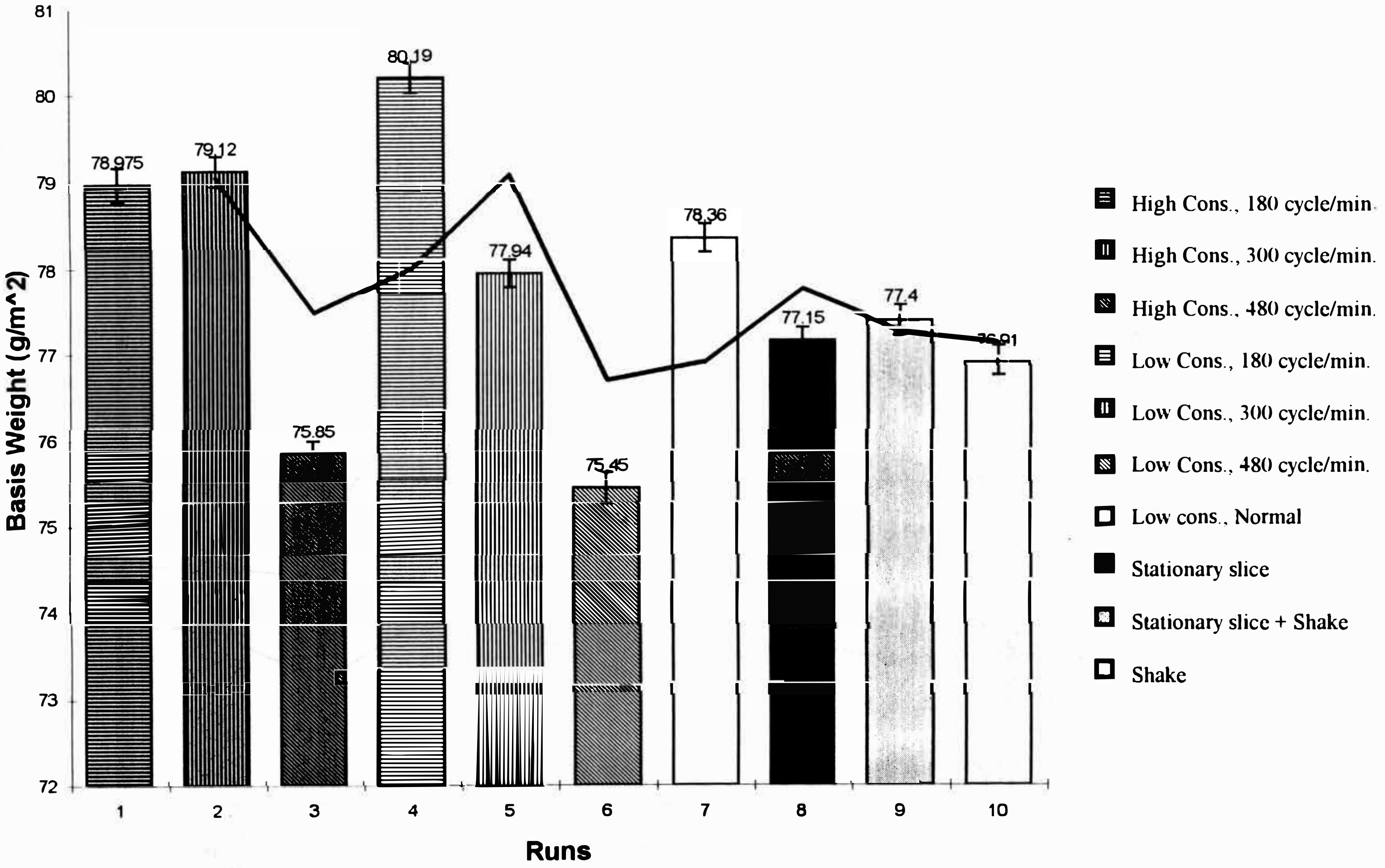


Figure 5. Basis Weight and Stock Flow Vs. Runs

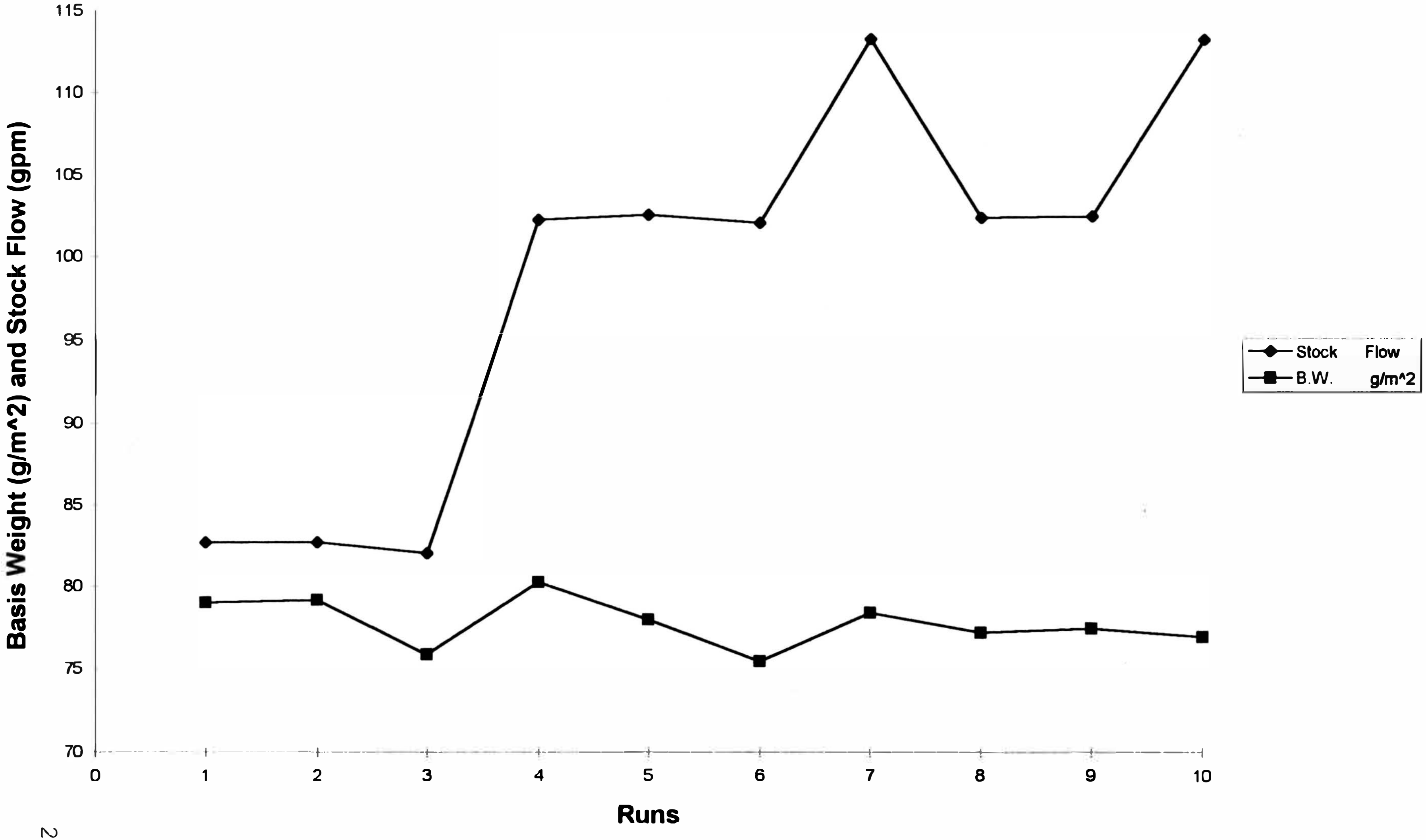
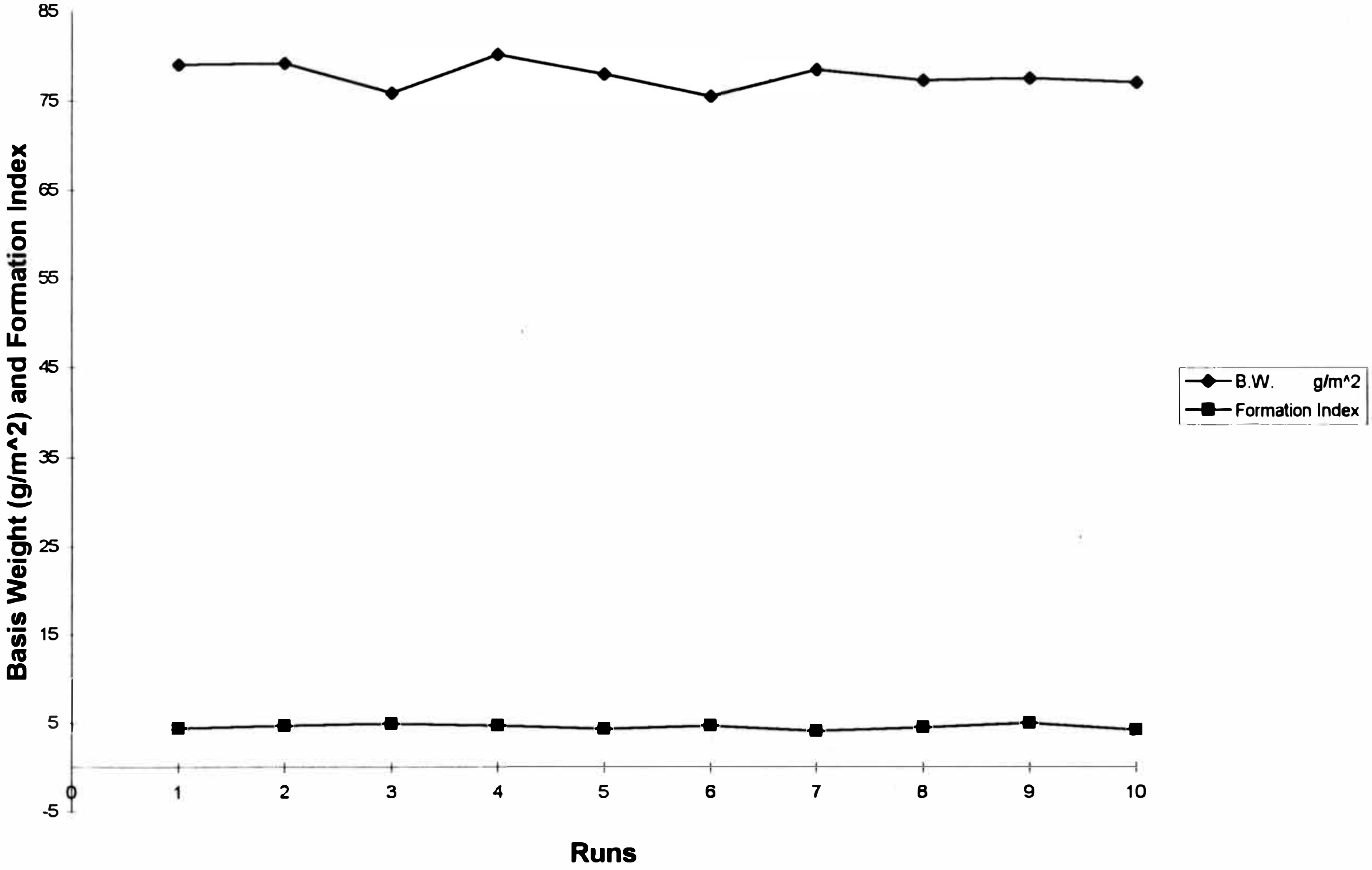


Figure 6. Basis Weight and Formation Index Vs. Runs



MD and CD Tensile Indices

Tensile strengths are based on a large testing specimen, which may contain variations in fiber concentration and orientation. Tensile strengths are predominant when fiber concentrations are uniform throughout the testing specimen i.e. formation. The tensile strengths are also greater in the direction of which the higher percentage of fiber in the testing specimen are aligned.

In the normal machine run, the only fiber defloccation occurring was generated by the contraction from within the headbox to the slice opening, which is 10 times larger than the longest fiber. The lack of dispersion allowed flocs that were created within the headbox, along with what was formed on the wire, to pollute the resulting sheet and therefore create poor formation indices. Because of the weak link concept, poor formation will be detrimental to tensile strengths. High MD fiber orientation, characteristic of this run, resulted in high MD tensile indices between the methods. The combination of poor formation and high MD fiber orientation resulted in the seen low CD tensile index of this run (seen in Figures 7, 8 and 9).

Applying the shake at a low machine speed will create fine scale turbulence that will penetrate from the bottom of the pulp suspension. These fine scale turbulences may disrupt formed flocs and possibly keep them from forming. Formation indices seen for the shake run were slightly improved over the normal machine run (seen in Figure 7, 8 and 10). The shake should have little affect on fiber orientation so the slight increase in formation could possibly increase both MD and CD tensile indices. The results show an increase in CD tensile indices and a slight decrease in MD tensile indices(seen in Figure 7 and 8). These small variations are within the standard deviation and therefore, it can be said that little occurred as the shake was applied to the wire. The frequency was not recorded, but appeared to be quite low. A higher shake frequency may have produced more favorable and expected formation

The stationary serrated slice is designed to specifically increase CD fiber orientation. The basic mechanism is intended to create shear forces in the CD by collapsing formed ridges in the pulp suspension. These shear forces create short life fine scale turbulences, that leave fibers in the resulting sheet in the CD. Orientating fibers in the CD causes a reduction in MD fiber orientation, resulting in a sheet with a higher degree of squareness. As seen in the stationary serrated slice run, both formation and sheet squareness were improved over the normal machine run(seen in Figure 10).

Adding the shake to the stationary serrated slice run seemed to produce shear at the wire (bottom of pulp suspension) in combination with the shear from the serrated edge, which possibly created longer lasting fine scale turbulence further down the wire, resulting in better formation. As seen from the results (Figures 7,8,9 and 10) MD, CD, and MD/CD tensile indices were very similar to the serrated slice run. Formation, on the other hand, was slightly improved with the addition of the shake to the stationary serrated slice.

Vibrating the serrated slice without the shake, allowed for much higher oscillating frequencies with respect to the wire speed, thus creating more intense, longer lasting, fine scale turbulence to the pulp suspension. Two levels of consistencies were run. If the speculations that were made when analyzing the basis weight behavior as slice frequency increased are true, then formation dependent paper properties should support better formation at the high consistency. As stated earlier, tensile indices increase either from the increase of fiber orientation in the tested tensile direction or formation is improved. If formation is fixed then an increase in either MD or CD tensile index without improved fiber orientation in the respective direction will support any improvements in formation. Although zero span tensile is a test of the tensile strength along a line in a given sheet, it measures all fibers crossing the testing line. There is no real definite way to tell if the lower MD and CD tensile indices at the higher consistency, high frequency (seen in Figure 7 and 8) are a result of fiber orientation. Therefore, within their respective standard deviation, the tensile indices between the low and high consistencies can be said to be equal. These conclusions support the better formation index at the high consistency, high frequency run. There is one other possible explanation. It appears that the trend between the low and medium frequencies of the high consistency MD tensile index runs were broken at the high frequency. This may be a result of poor sampling or testing technique. It appears that at both consistencies, the degree of sheet squareness improved as the frequency was increased.

Figure 7. MD Tensile Index Vs. Runs

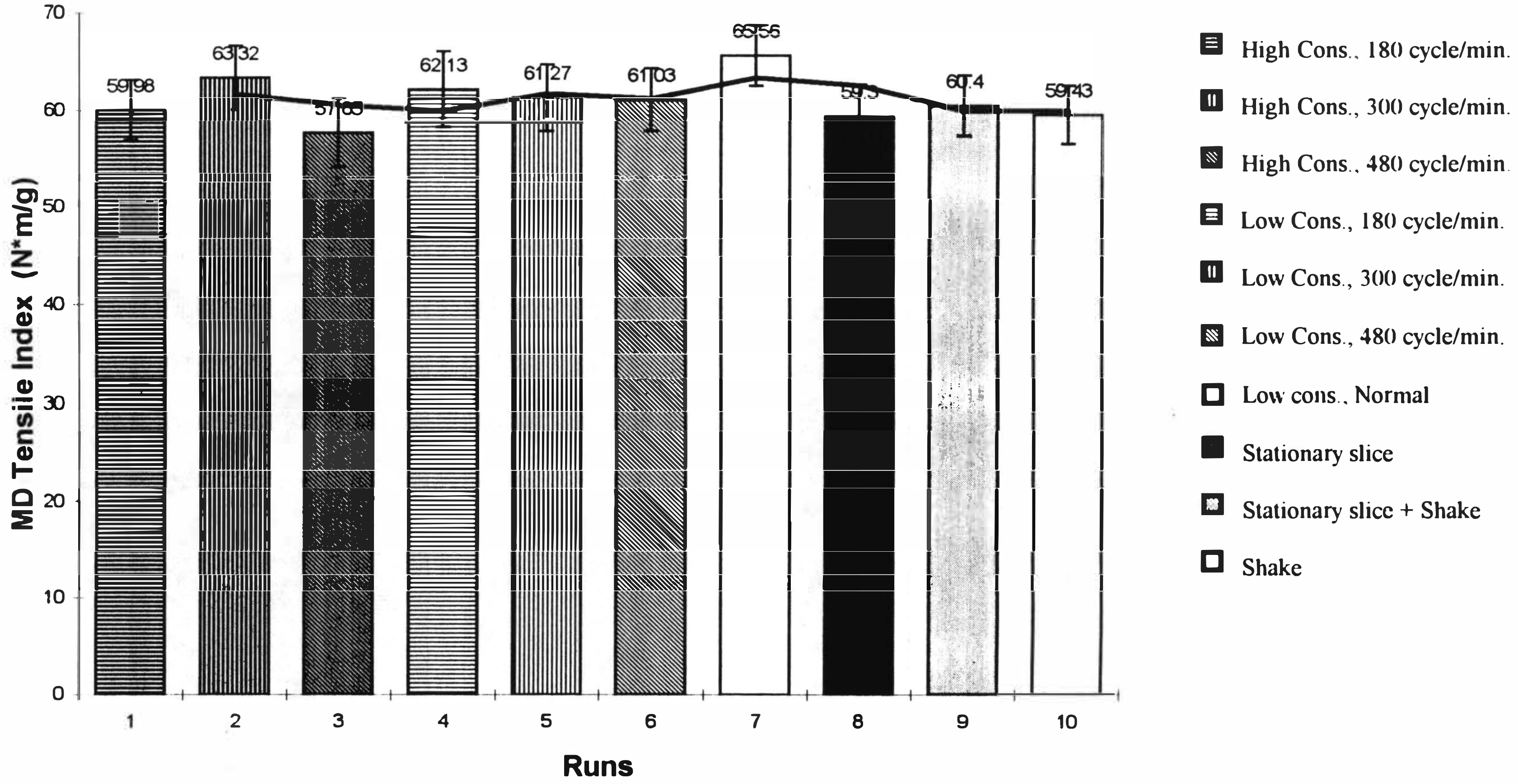


Figure 8. CD Tensile Index Vs. Runs

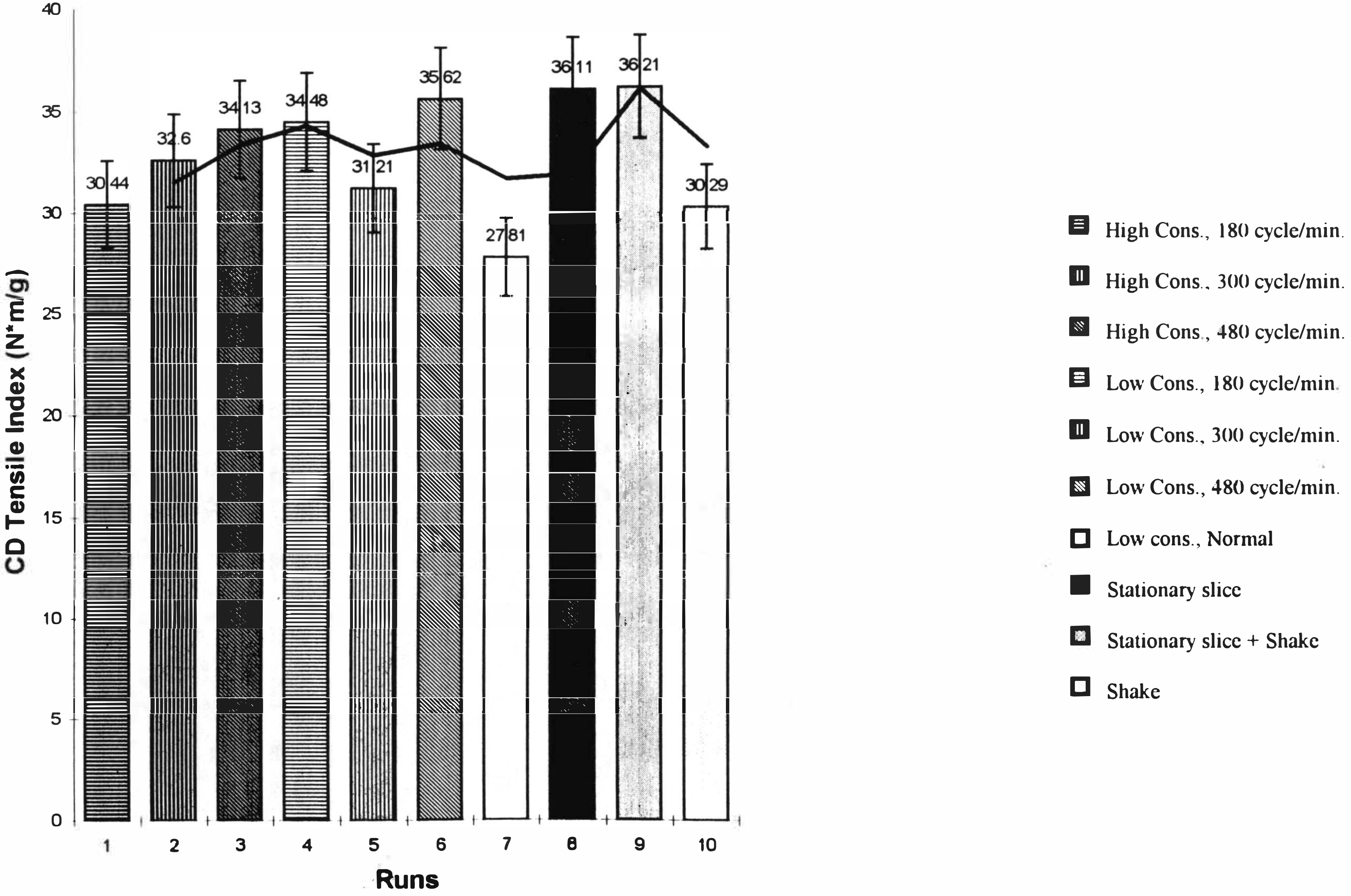


Figure 9. MD/CD Tensile Index Vs. Runs

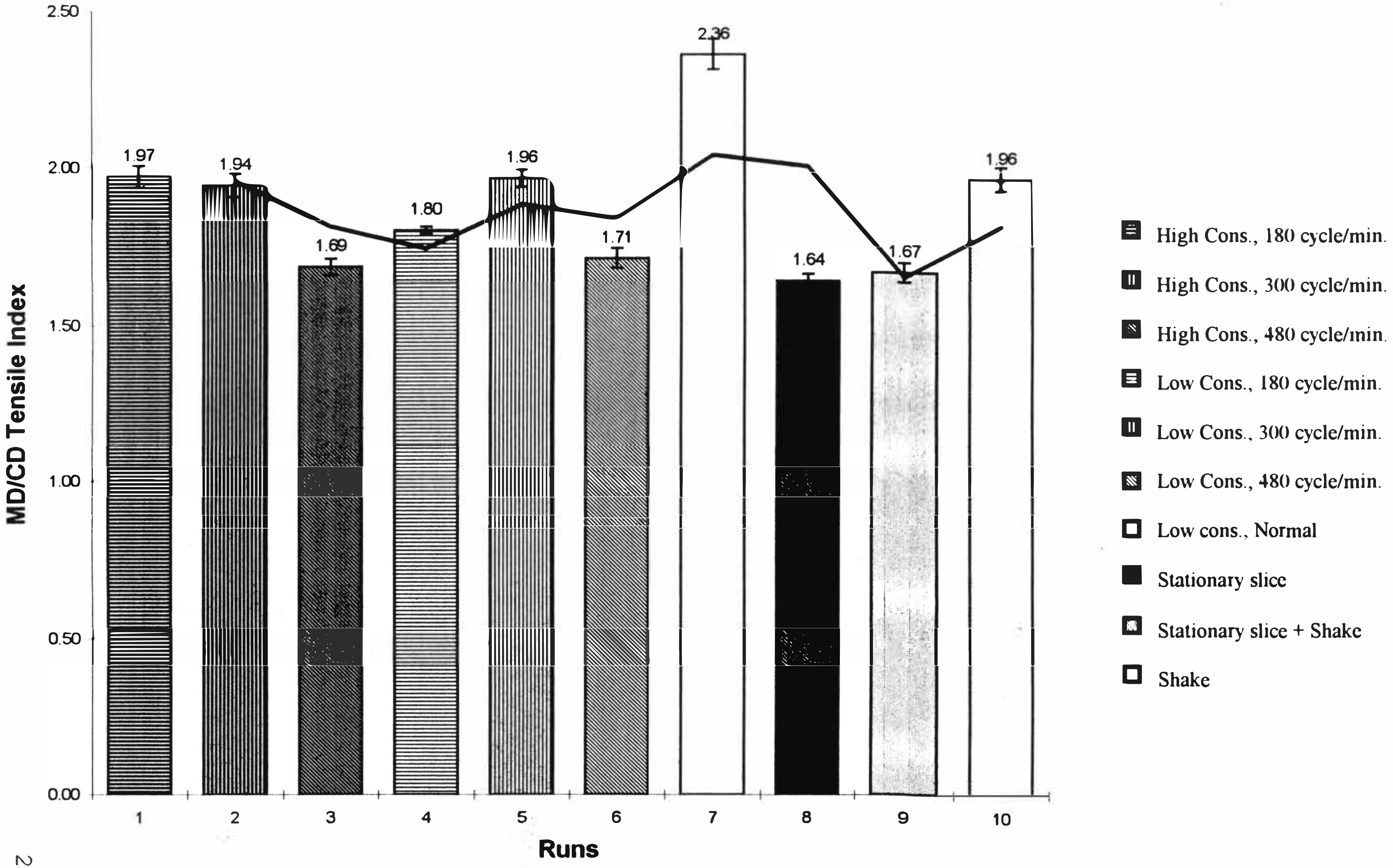
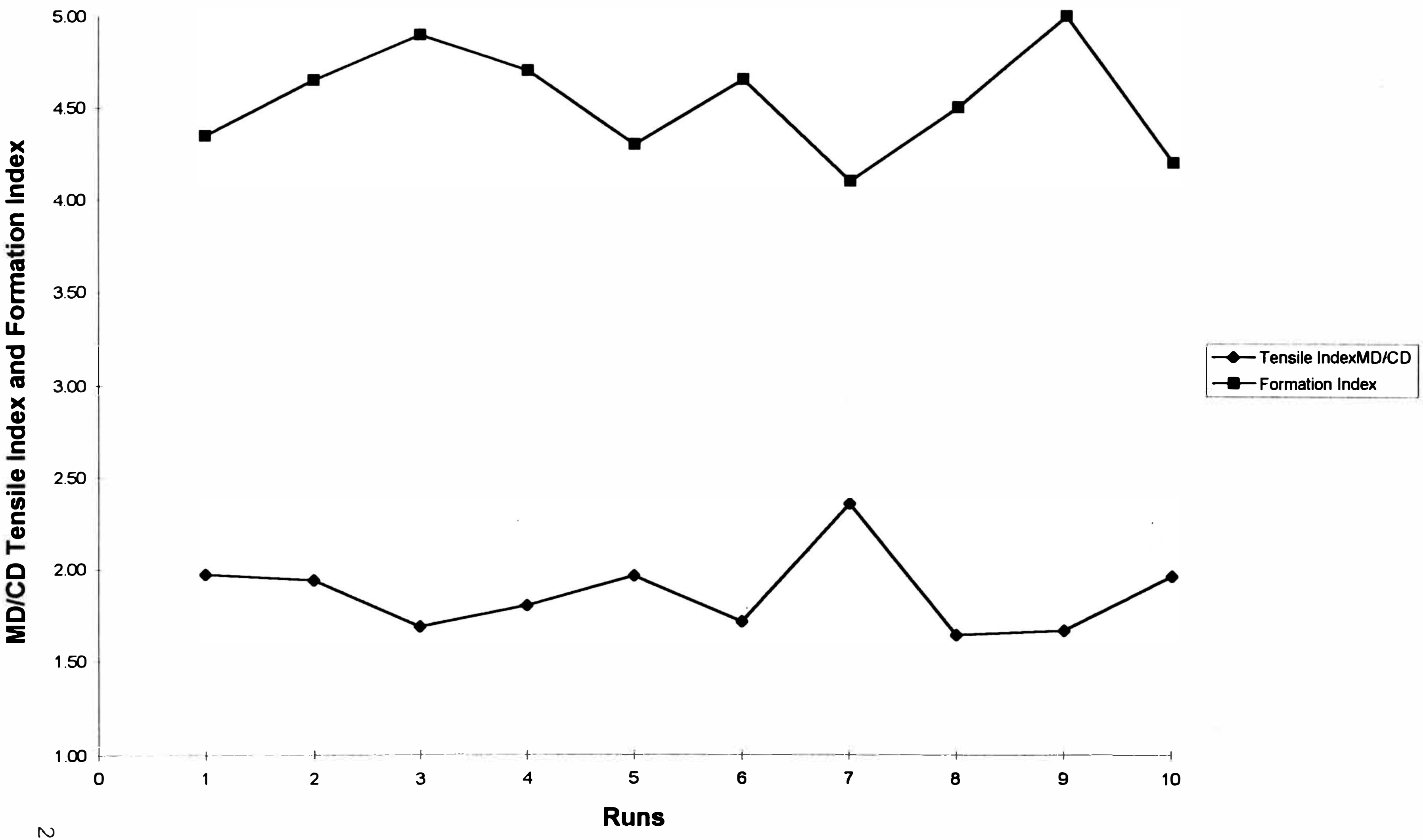


Figure 10. MD/CD Tensile Index andFormation Index Vs. Runs



Zero Span Tensile

The zero span tensile measurement will give a relative strength of the individual fiber and the tensile value will vary due to the number of fibers in the test. A zero span tensile ratio will then give an indication of the degree of fiber orientation. Similar to the tensile index, as the MD/CD ratio approach unity, the higher the degree of sheet squareness there is. The results in Figure 12 show that formation is affected by the degree of sheet squareness. The higher the degree of sheet squareness, the better the formation for all methods.

Figure 11. MD/CD Zero Span Tensile Vs. Runs

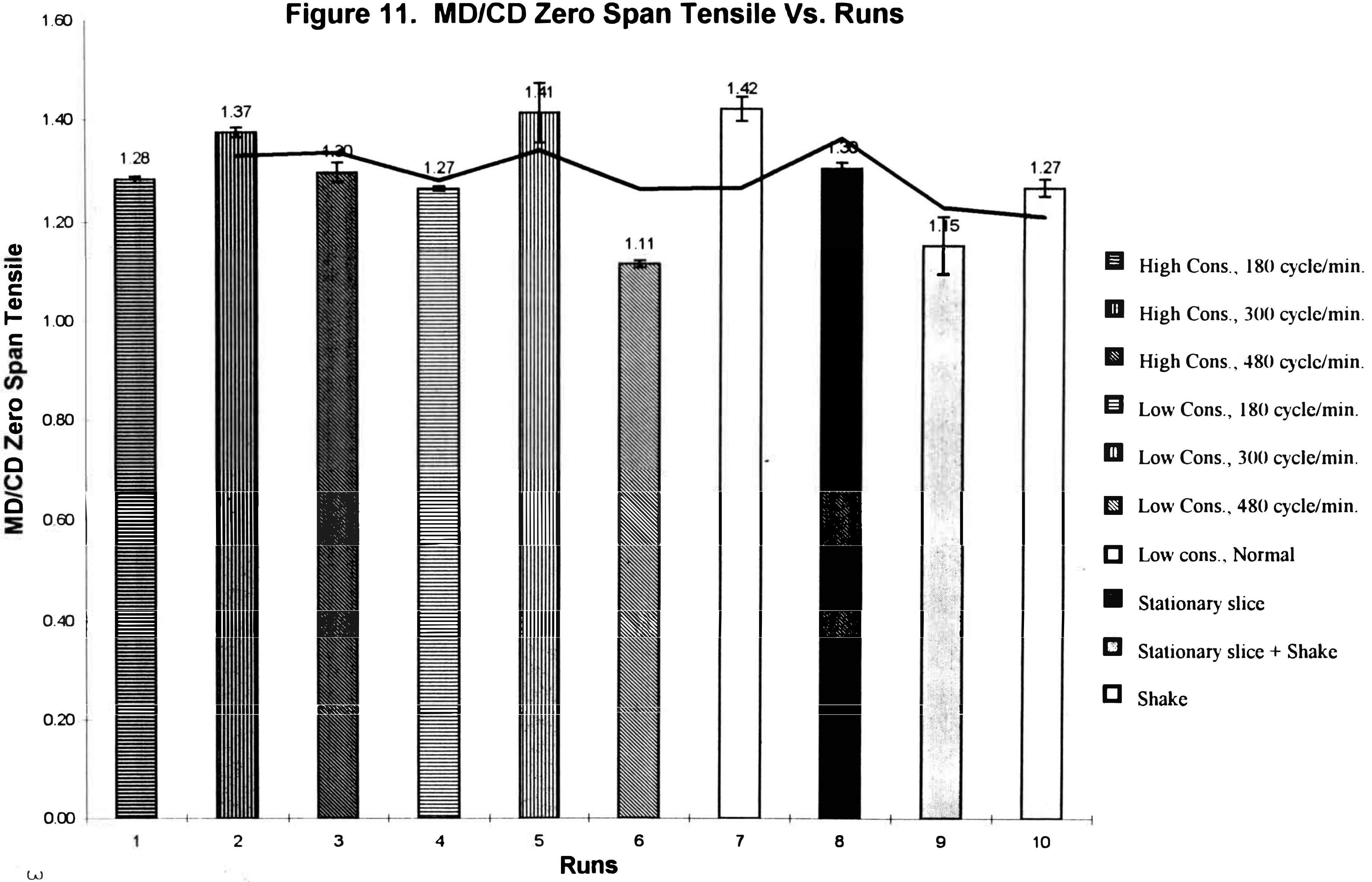
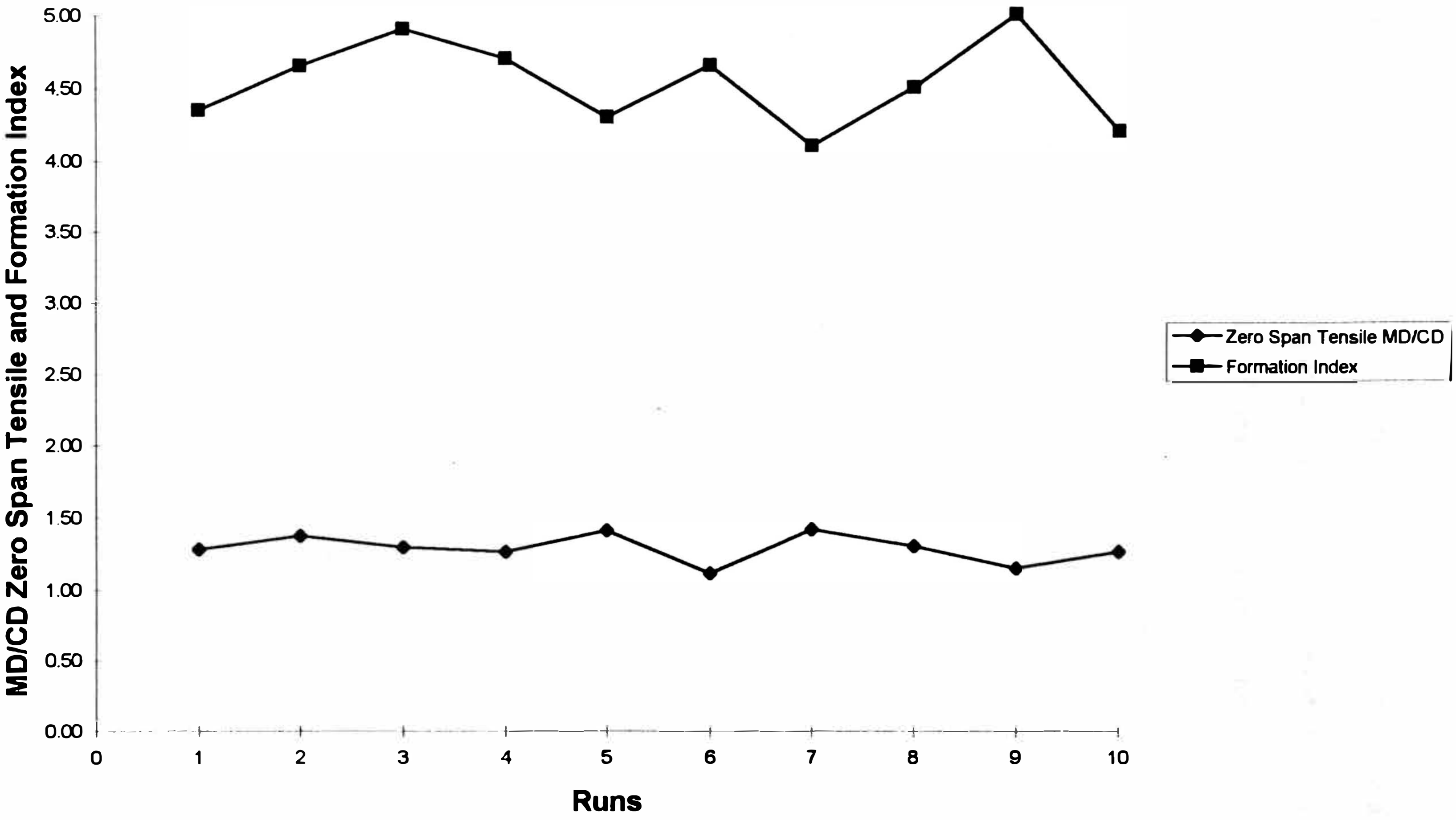


Figure 12. MD/CD Zero Span Tensile and Formation Index Vs. Runs



Opacity Deviation

As mentioned earlier in the experimental procedure, opacity deviations can be examined as an indication of formation quality. The higher the formation quality, the lower the deviation. Results Figures 13 and 14 show opacity deviations decreased as formation index increased for all methods.

Figure 13. Opacity Deviation Vs. Runs

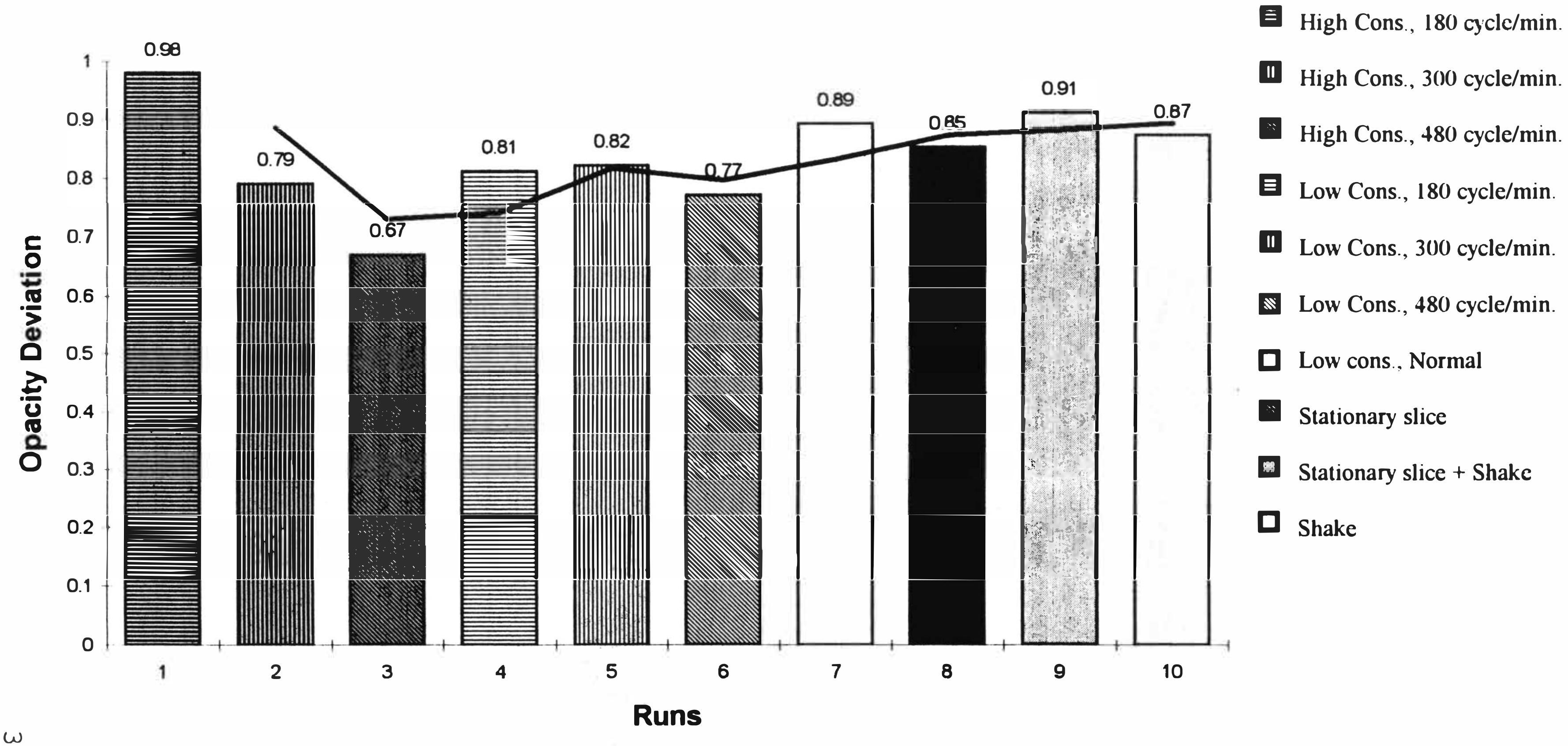
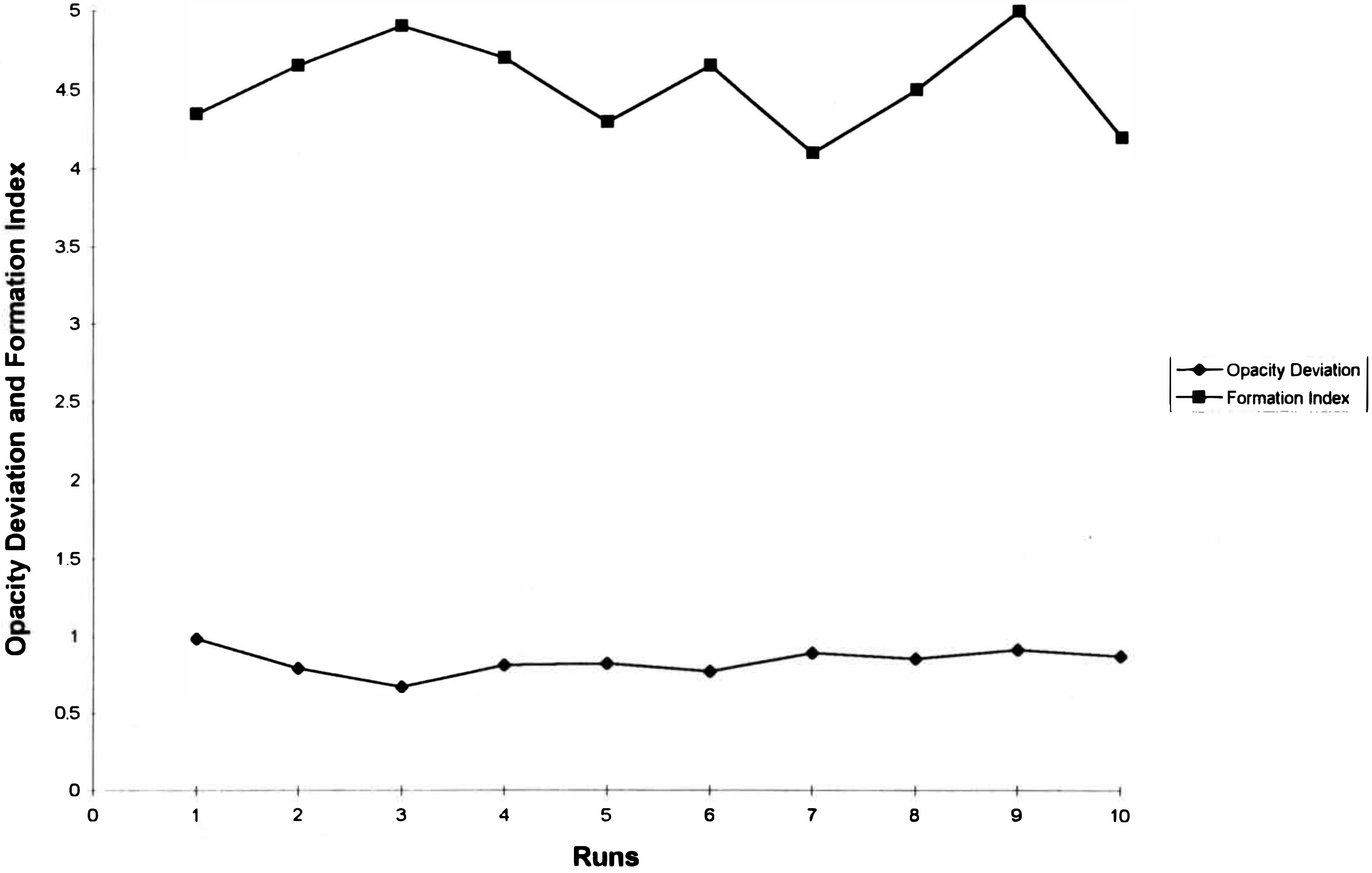


Figure 14. Opacity Deviation and Formation Index Vs. Runs



CONCLUSIONS

Serrated slice frequencies with oscillating velocities closer to 50% of the machine speed, at both low and high consistency levels showed significant improvements in formation over the normal machine run (control run). However, as the slice velocity approached 50% of the machine speed, fiber retention on the wire significantly decreased. In general, this loss of retention is not favorable. In this case, the loss of retention resulted in a lower basis weight, therefore, reducing the oven dry fiber required in the final sheet.

The hydraulic shear created by the vibrating serrated slice appeared to increase the degree of sheet squareness. This was seen in the improved formation and fiber orientation properties in the resulting sheet.

The shake method on the machine is thought to be the best known method at improving sheet formation at speeds less than 400 ft./min. The specially designed vibrating serrated slice used for this study was able to improve sheet formation and sheet squareness at both low and high headbox consistency at speeds of 70 ft/min.. The higher headbox consistency and lower basis weight supported the primary objective of reducing material and energy usage, while preserving or improving formation and formation properties.

In the vibrating serrated slice runs, the recirculation of fines and shorter fibers that flow from the wire pit to the headbox were determined to have little affect of the subsequent runs. This determination was based on the unsteady state nature of the machine trial. If the system were under steady state conditions, the concentration of fines and shorter fiber in the wire pit would increase. The recirculation in this case would change the initial furnish characteristics in the headbox, therefore, affecting paper properties of subsequent runs.

RECOMMENDATIONS

The following recommendations are essential for further studies of the serrated slice on improving formation:

1. A better control of the headbox consistency and the basis weight to enhance the understanding of the sheet forming process of the vibrating serrated slice method.
2. A further study on the effects of the vibrating serrated slice at higher then normal headbox consistencies should be completed. The conclusion showed that it may be beneficial to use this device, but more confidence is needed.
3. A further study on the effects the vibrating serrated with different long fiber furnishes and grades.
4. A look at varying the vibrating serrated slice oscillating amplitude to obtain finer scale turbulence to the pulp suspension.

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Appendix I

Machine Runs

Run	Shake	Slice	Cons.	B.W.	Freq. cycle/min.	Slice opening	Meas. Cons.	Mach Spd.	Stock Flow
1		Vib.	0.90%	50lb	480	1.5 in.	0.60%	70.9	87.5
2		Vib.	0.90%	50lb	**300**	1.5 in.	0.60%	70.9	87.7
3		Vib.	0.90%	50lb	180	1.5 in.	0.60%	70.9	82.6
4		**Vib.**	**0.90%**	50lb	180	**1.25 in.**	**0.60%**	**70.9**	**82.7**
5		**Vib.**	**0.90%**	50lb	**300**	**1.25 in.**	**0.60%**	**70.9**	**82.7**
6		**Vib.**	**0.90%**	50lb	480	**1.25 in.**	**0.60%**	**70.9**	**82**
6b			0.90%	50lb		**1.25 in.**	0.60%	70.9	82
7		Vib.	0.70%	50lb	480	**1.25 in.**	0.48%	70.9	87.3
8		Vib.	0.70%	50lb	**300**	**1.25 in.**	0.48%	70.9	87.5
9		Vib.	0.70%	50lb	180	**1.25 in.**	0.48%	70.9	87
10		Vib.	0.70%	50lb	180	1.5 in.	0.48%	70.9	87
11		Vib.	0.70%	50lb	**300**	1.5 in.	0.48%	70.9	87.2
12		Vib.	0.70%	50lb	480	1.5 in.	0.48%	70.9	87.2
12b			0.70%			1.25 in.	0.48%	70.9	87.2
13		Vib.	0.50%	50lb	480	1.5 in.	0.40%	70.9	101.3
14		Vib.	0.50%	50lb	**300**	1.5 in.	0.40%	70.9	101.8
15		Vib.	0.50%	50lb	180	1.5 in.	0.40%	70.9	101.6
16		**Vib.**	**0.50%**	50lb	180	**1.25 in.**	**0.40%**	**70.9**	**102.2**
17		**Vib.**	**0.50%**	50lb	**300**	**1.25 in.**	**0.40%**	**70.9**	**102.5**
18		**Vib.**	**0.50%**	50lb	480	**1.25 in.**	**0.40%**	**70.9**	**102**
18b			**0.50%**	50lb		**1.25 in.**	**0.40%**	**70.9**	**102**

Unscheduled Runs

Run	Shake	Slice	Cons.	B.W.	Freq. cycle/min.	Slice opening	Meas. Cons.	Mach Spd.	Stock Flow
19		Stat	0.50%	50lb		1.5 in.	0.40%	70.9	102.3
20		**Stat.**	**0.50%**	50lb		**1.25 in.**	**0.40%**	**70.9**	**102.3**
21	**Shake**	**Stat.**	**0.50%**	50lb	**High**	**1.25 in.**	**0.40%**	**70.9**	**102.4**
22	**Shake**	Stat.	0.50%	50lb	High	1.5 in.	0.40%	71.2	102.3
23	**Shake**		0.50%	50lb	High	1.5 in.	0.40%	71.2	113.2
24	**Shake**		**0.50%**	50lb	**High**	**1.25 in.**	**0.36%**	**71.2**	**113.2**
25			**0.50%**	50lb		**1.25 in.**	**0.36%**	**71.2**	**113.2**

Appendix II

Machine Runs for Final Analysis

Initial Run	Run	Shake	Slice	Cons.	B.W.	Freq.	Slice Opening	Meas. Cons.	Mach Spd.	Stock
4	1		Vib.	0.90%	50lb	180	1.25 in.	0.60%	70.9	82.7
5	2		Vib.	0.90%	50lb	300	1.25 in.	0.60%	70.9	82.7
6	3		Vib.	0.90%	50lb	480	1.25 in.	0.60%	70.9	82
16	4		Vib.	0.50%	50lb	180	1.25 in.	0.40%	70.9	102.2
17	5		Vib.	0.50%	50lb	300	1.25 in.	0.40%	70.9	102.5
18	6		Vib.	0.50%	50lb	480	1.25 in.	0.40%	70.9	102
25	7			0.50%	50lb		1.25 in.	0.36%	71.2	113.2
20	8		Stat.	0.50%	50lb		1.25 in.	0.40%	70.9	102.3
21	9	Shake	Stat.	0.50%	50lb	High	1.25 in.	0.40%	70.9	102.4
24	10	Shake		0.50%	50lb	High	1.25 in.	0.36%	71.2	113.2

Appendix III

Consistency Calculation

Basis: 50/50 hardwood/softwood = 220 lb. O.D. fiber

At 0.4% consistency

Water required = (220lb fiber /.004) - 220 lb. fiber = 54,780 lb. water

At 0.6% consistency

Water required = (220 lb. fiber / 0.006) - 220 lb. fiber = 36,446 lb. water

Percent difference at the higher consistency

% difference = (54,780 - 36,446 / 54,780) * 100 = 33.5%

Gallons of water less needed at the 0.6% consistency

gallons = (54,780 lb. water-36,446 lb. water)*(1 ft^3 / 62.4 lb.)*(7.48 gal / 1 ft^3)

= 2,200 gallons

Appendix IV

Serrated Slice
Frequency Calculation

Assume machine speed = 70 ft/min.

Max. slice velocity = 0.50 * 70 ft/min. 35 ft/min.

Slice edge period = 0.75 in.

Oscillating slice amplitude = 0.75 in. / 2 = 0.375 in.

Slice travel in one cycle = 0.375 in. * 2 = 0.75 in. / cycle

Max. frequency = (35 ft/min.)/ (0.75 in./ 12) = 560 cycles / min.

Machine trial frequency:

High (85% of max.) = 476 cycles / min.

Medium (55% of max.) = 308 cycles / min.

Low (30% of max.) = 168 cycle / min.