IPST Technical Paper Series Number 590

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August 1995

Submitted to
Journal of Pulp and Paper Science

ACOUSTO-OPTICAL METHOD FOR MEASURING WET FIBER FLEXIBILITY

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ABSTRACT

A novel method to determine wet fiber flexibility using high-power ultrasonics was investigated. The radiation force of an ultrasonic traveling wave field was used to consolidate a pulp suspension into a mat and then elastically compact the mat. The amount of elastic compaction was determined using an image analysis system. Compaction experiments, performed on a Kraft market pulp beaten to various levels, were shown to correlate linearly with the pulp's handsheet density and strength.

INTRODUCTION

Wet fiber flexibility (WFF), which defines how easily a wet fiber bends, affects every optical and physical property of paper, making it one of the most important properties to papermakers [1]. Despite this importance, wet fiber flexibility is seldom measured to control the papermaking process, because the available measurement methods are not suitable for a mill environment and are not easily adaptable for on-line testing.

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Review of the literature shows that many individual fiber and ensemble property methods have been developed to determine the flexibility of wood pulp fibers. Methods involving the bending of single fibers using mechanical or hydrodynamic forces can provide very accurate measurements [2-6]. However, they have severe limitations because they can only test a single fiber at a time and many tests are necessary to obtain a population average. Moreover, they are unsuitable for very short fiber testing.

Another approach which has seen a constant stream of improvements over the years relates to the flexibility evaluation of dry fibers draped over a glass rod on a glass slide [7-12]. Determination of how much the fibers bent during drying is done by measuring the amount of optical contact between the slide and the fibers. Whereas this approach is able to measure the flexibility of many fibers with a single test, results may be sensitive to other fiber properties. The testing procedure would be difficult to modify for on-line implementation.

Other types of flexibility tests have been developed using fundamental modes of vibration [13,14] and structural methods [15]. More recently, fiber suspension flow methods involving fibers passing through a slot perpendicular to a laminar flow channel have been devised [16,17]. Dilution is required to allow single fiber detection using an imaging system. The flow methods provide a noncontact means to classify a population of fibers. Observations using fiber-fine mixtures have not been reported.

The present work proposes a novel method to determine the mean wet flexibility of a fiber suspension. The method is based on the degree of compaction of a fiber suspension subjected to an ultrasonic traveling wave field. It is hypothesized that acoustically-induced fiber compaction under an elastic regime is related to wet fiber flexibility. The degree of compaction can be determined by optical means. Adaptation to part of a flow loop in a stock line for on-line monitoring can be envisioned because the use of an acoustic force to compact flowing fibers excludes physical contacts.

Measurement principles and a description of the experimental methodology to determine the degree of acoustic fiber compaction are next presented. Then, results relating the degree of compaction to sheet parameters sensitive to wet fiber flexibility are reported and discussed. The concept of a possible on-line implementation is also discussed.

MEASUREMENT PRINCIPLES

Consider a short section of a square cross-sectional channel flow in which two of the walls are replaced by an ultrasonic transducer and a sound absorber. These two elements are mounted on opposite sides so that, when the transducer is energized, a traveling (unidirectional) wave field propagates from the transducer to the absorber and the acoustic energy is fully absorbed by the absorber.

If a stationary fiber suspension is located in the modified channel flow section, it will interact with the traveling wave field in such a way that the fibers will move away from the transducer and be pushed against the absorber. This migration effect is similar to that found in some earlier work related to the agglomeration of water suspended fibers in an ultrasonic standing wave field [18,19]. Depending upon the level of acoustic power, the suspension will quickly consolidate into a mat at the surface of the absorber. The compaction phenomenon is best appreciated by referring to Fig. 1. This figure illustrates the geometry of the transducer-absorber assembly and the location of the compacted fiber mat at the surface of the absorber. Assuming that all fibers are part of the compacted mat, pure water stands between the transducer and the mat.

Now, if the compacted mat is no longer subjected to the traveling wave field, it will tend to spring back due to the residual elasticity of the fiber network. Under cyclic conditions for which the field is turned on and off continuously, the fiber mat will compress and expand. Compression and expansion can be indefinite if an elastic regime exists. Using an appropriate imaging technique, compressed and expanded fiber mats can be detected and the degree of compaction can be quantified.

EXPERIMENTAL METHODOLOGY

Experimental Setup

A schematic diagram of the experimental setup is shown in Fig. 2. The apparatus consists of a flow loop to provide a uniform consistency and constant temperature pulp slurry (whole pulp) to an acoustic cell mounted in a 2-cm x 2-cm cross-sectional channel flow. Tap water is used as the supporting medium. The cell height, and therefore, the transducer-absorber assembly length are 10 cm (see Fig 1). The transducer is made of several layers of a piezoelectric ceramic material; it is custom-designed to resonate at 150 kHz. The sound absorber is manufactured out of elastomer, nickel powder, and acrylic microballoons. Glass windows normal to the transducer-absorber assembly are used for illumination and imaging purposes. At the onset of transducer excitation using a computer-controlled high-power AC source, a traveling wave field is produced in the acoustic cell. A miniature PVDF hydrophone can be mounted on a 3-D translation stage located above the cell (not shown) to evaluate field uniformity and to determine the level of acoustic power anywhere in the cell.

The amount of fiber mat compaction is captured using a CCD camera. An incandescent light source is used to provide backlit illumination. Measurements are accomplished as follows. First, the system captures and measures the area of a projection of the backlit fiber mat when the acoustic field is on. Then, the field is turned off, and a second image of the mat is captured and measured. The difference between the areas of the two images is the amount of elastic compaction, i.e., A_{Comp}. The consolidation area of the mat, A_{Cons}, as measured from the second image, is used to normalize the compaction area. The resulting ratio of the compaction area to the consolidation area is defined as percent compaction as indicated in Eq. 1. This parameter is analogous to percent strain of a tensile test.

$$\%\ Compaction = \left(\frac{A_{Comp}}{A_{Cons}}\right)100 \qquad (1)$$

An example of the images obtained during a typical test is shown in Fig. 3. Fiber mat projected areas when the acoustic power is a) on and b) off are identified by the gray areas. Black areas refer to pure water projected areas. When comparing a) and b), it is clear that the fiber mat is compacted when the acoustic power is turned on. The acoustic technique is very good as far pulp thickening is concerned. In this particular case, the pulp consistency was set to 1%, and the mat consistency is almost twice as much when the acoustic power is on. Fig. 3c shows the compacted area (vertical dark band), which was obtained for illustrative purposes using an "Exclusive-OR" operation on a) and b). Dark pixels in c) correspond to the same positions but different intensity pixels in a) and b). A more quantitative approach was actually followed to determine the compacted and consolidated areas.

Sample Preparation, Characterization, and Testing

Reported results were obtained using a market bleached Kraft softwood pulp. This pulp was beaten to various levels in a Valley beater according to TAPPI standard T205. Samples taken at each level were tested for CSF. A preliminary series of experiments was first conducted to optimize experimental conditions for compaction observations. Results were obtained at acoustic power levels of approximately 2.5 and 5.6 W_{RMS} and pulp consistencies of 0.5 and 1.0 %. The flow loop system did not allow satisfactory testing at consistencies in excess of 1%. Measurements were repeated five times for each set of conditions. In order to gather some insights about the meaning of percent compaction data, 200 g/m^2 handsheets were prepared. Density was measured, and tensile (TAPPI standard T494) and burst (TAPPI standard T403) tests were performed. The handsheet properties are shown in Table 1.

RESULTS AND DISCUSSION

Values of percent compaction at 5.6 W_{RMS} acoustic power, and 0.5 and 1% consistency are shown plotted against handsheet density in Figs. 4 and 5, respectively. Tensile index results are displayed in Figs. 6 and 7. Excellent correlations are obtained in all cases, including burst strength (not shown). Data suggest linear relationships. However, this is not firmly established, and additional observations are required to support this claim.

Since wet fiber flexibility is one factor that increases handsheet density and strength, it is hypothesized the test gives some measure of this fiber property. Consistency does not show any effect on the measurements as is expected. This is attributed to the acoustic force consolidating the pulp suspension into a mat before the elastic compaction. When comparing measurements obtained at 2.5 and 5.6 W_{RMS}, the larger power was able to produce a greater percent compaction, also as expected since this power level translates to a larger acoustic force. The available equipment did not allow testing at larger acoustic power levels and, hence, conditions for higher compaction levels (elastic and inelastic regimes) could not be observed. One should note that a 5.6 W_{RMS} power level is a relatively low power.

Sources of Error

As seen in Figs. 4-7, error bars indicate that the measurements are repeatable. The largest source of error was due to the mat's not being uniformly compacted (see Fig. 3). This problem was due mainly to the nonuniformity of the traveling field and directly related to the transducer's properties, which were found to deteriorate during the course of the project. A more uniform and energy-efficient transducer would produce a very well-defined compacted area. As a matter of interest, a substantially improved and more reliable transducer has since been tested. Other lesser sources of errors were the resolution of the image analysis system (0.0765 cm^2), the three-dimensional mat's having been measured as two-dimensional projection, and gravity effects on the mat.

On-line Implementation

An on-line implementation would involve the detection of the percent compaction in a continuous mode. In this situation, flowing fiber suspensions would penetrate the acoustic cell and be gradually compacted as they move into it. Measurements would be collected near the exit of the acoustic cell, i.e., where the field provides maximum and stable compaction (analogous to Fig. 3a) and just out of it, i.e., where the fiber mat is released due to the absence of the field (analogous to Fig. 3b). Assuming that the measurements could be extended to cover the medium consistency range (up to 5%), dilution would not be required.

CONCLUSIONS

Compactibility experiments were performed using a traveling wave field to consolidate a pulp suspension into a mat and then elastically compact the mat. Percent compaction was measured taking the ratio of projected compaction area to consolidation area. Results from the compactibility experiments indicate that the percent compaction correlates with sheet properties of strength and density and does not appear to be sensitive to consistency variations. The method is believed to do this by measuring the wet fiber flexibility, although further verification from experiments using various furnishes is needed.

ACKNOWLEDGMENTS

The authors would like to acknowledge Member Companies of the Institute of Paper Science and Technology for their support.

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Table 1. Handsheet properties.

BEATING	CSF	APPARENT DENSITY		TENSILE INDEX		BURST STRENGTH	
TIME	LEVEL	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
(min)	(ml)	(g/cc)	(g/cc)	(Nm/g)	(Nm/g)	(psi)	(psi)
0	635	0.588	0.045	18.8	0.2	33.0	1.2
5	580	0.597	0.023	22.7	0.6	52.3	0.9
10	440	0.630	0.046	25.3	0.4	65.9	1.6
15	370	0.648	0.031	36.5	1.8	74.2	0.9
20	335	0.660	0.013	41.2	0.9	90.0	0.6

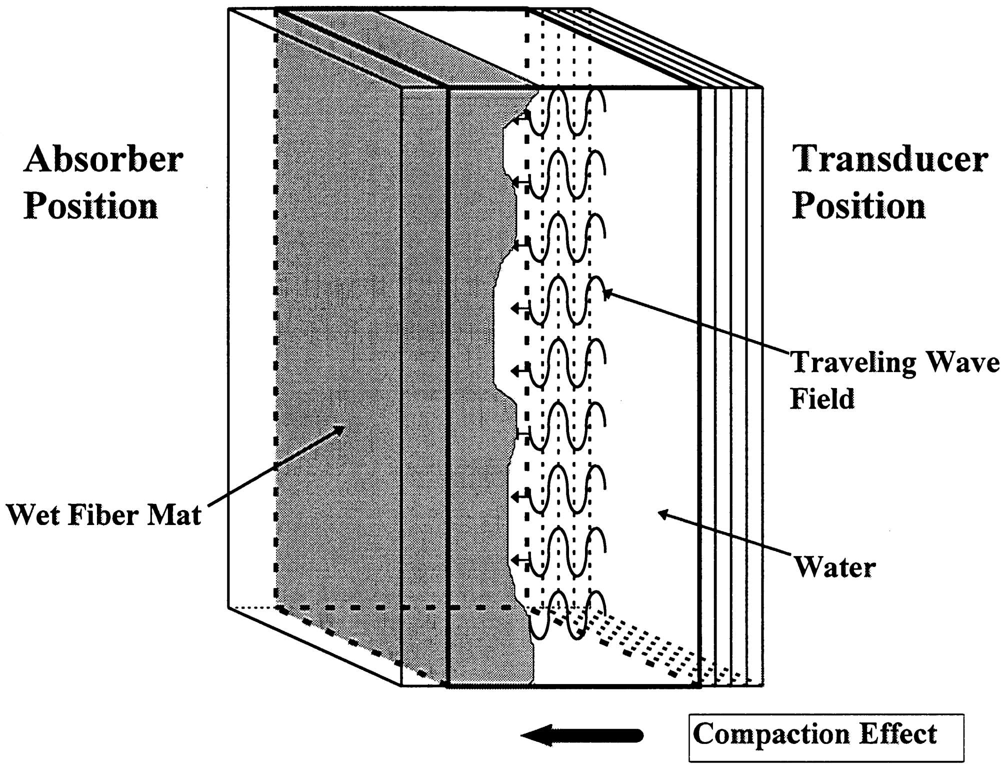


Fig. 1. Schematic diagram of the acoustic compaction phenomenon between the transducer and absorber positions.

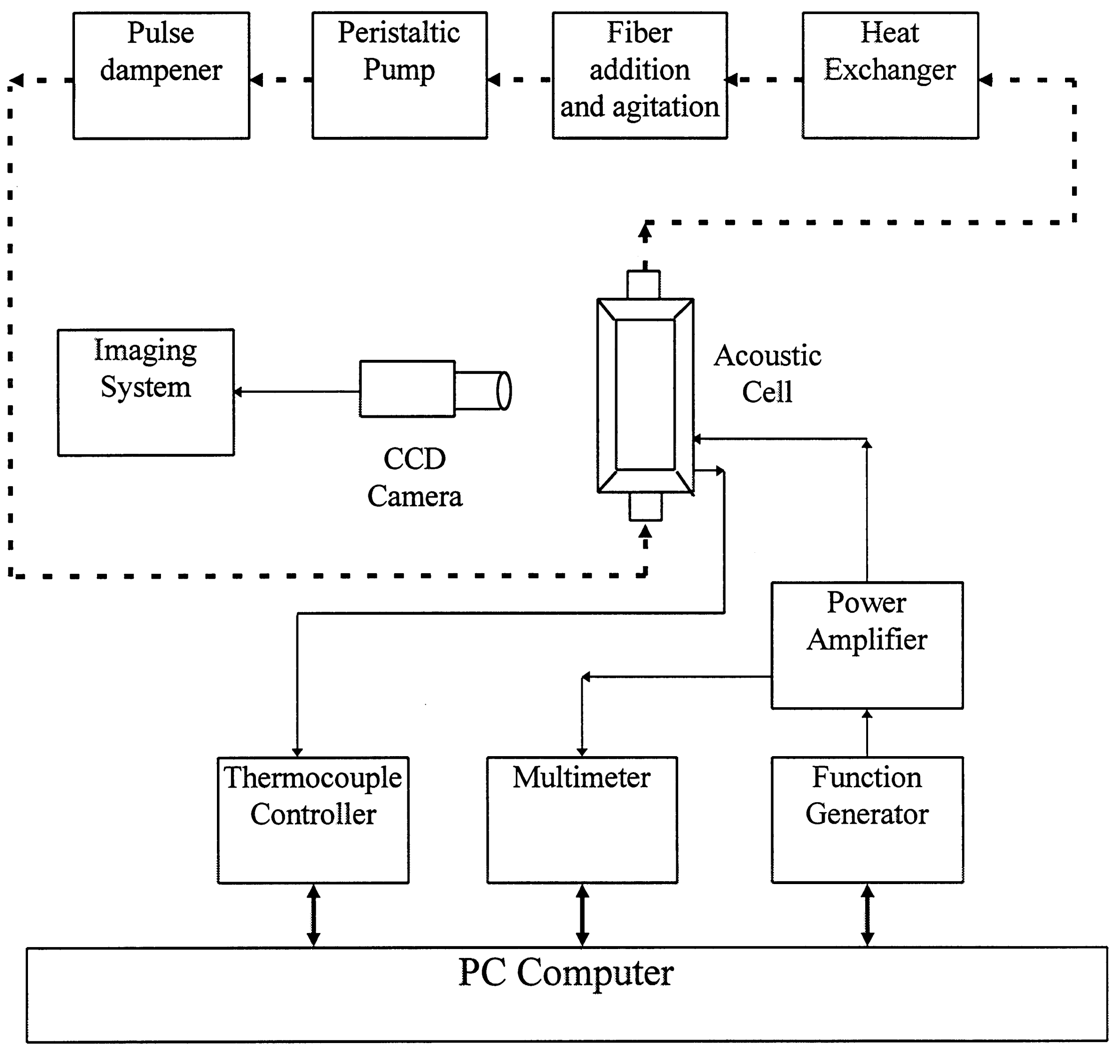
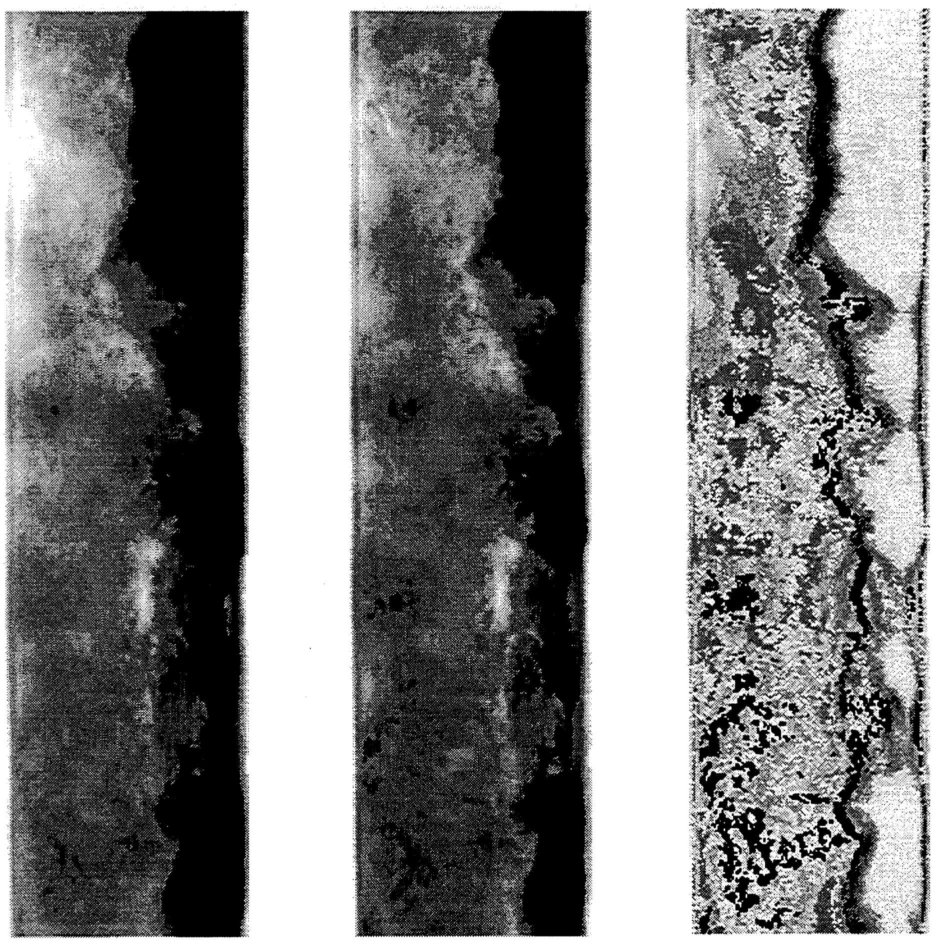


Fig. 2. Experimental apparatus flow diagram.



a) Acoustic Power on

b) Acoustic Power off

c) "Exclusive-OR" Operation

Fig. 3. Typical acoustic compaction results gathered using the imaging system. The absorber is located on the left side of a) and b).

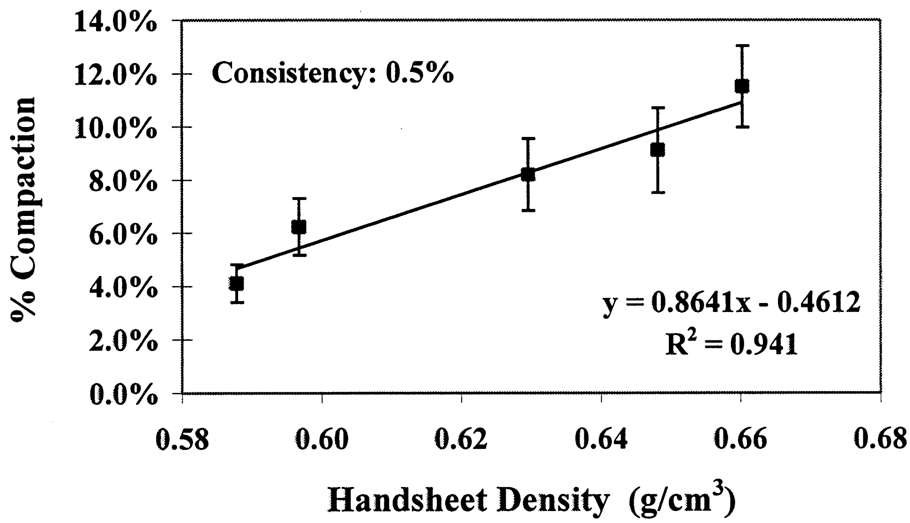


Fig. 4. Percent compaction vs. density at 5.6 W_{RMS} acoustic power and 0.5% consistency.

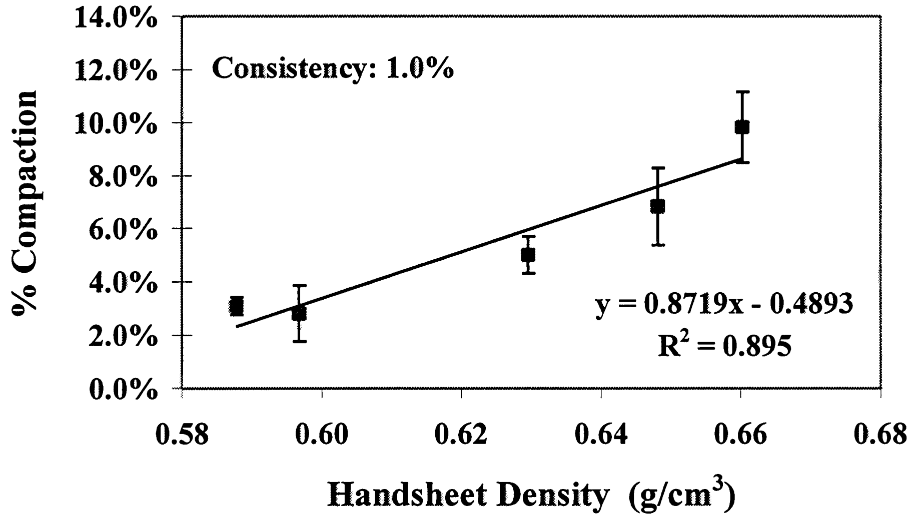


Fig 5. Percent compaction vs. density at 5.6 W_{RMS} acoustic power and 1.0% consistency.

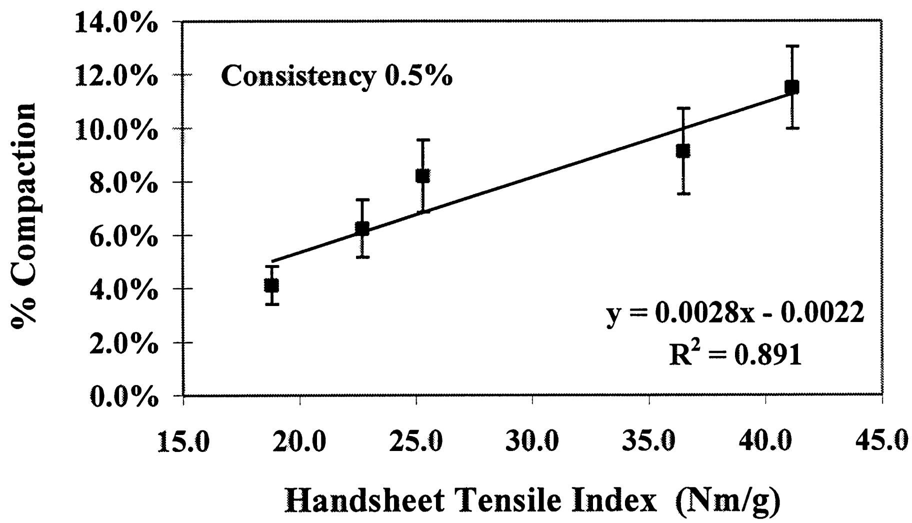


Fig. 6. Percent compaction vs. tensile index at 5.6 W_{RMS} acoustic power and 0.5% consistency.

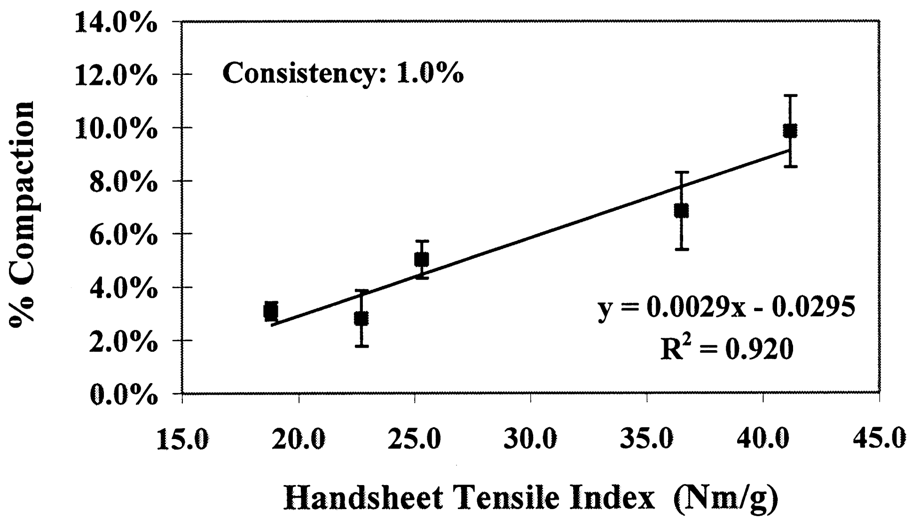


Fig. 7. Percent compaction vs. tensile index at 5.6 W_{RMS} acoustic power and 1.0% consistency.