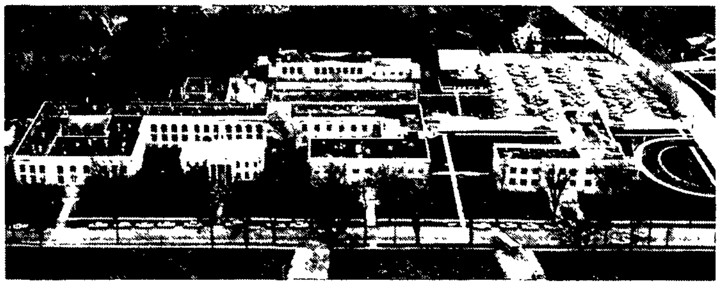

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ON-LINE MEASUREMENT OF PAPER MECHANICAL PROPERTIES

G. A. BAUM and C. C. HABEGER

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G. A. Baum and C. C. Habeger
The Institute of Paper Chemistry, P.O. Box 1039, Appleton, Wis. 54912

ABSTRACT

A device is described which is capable of measuring certain paper mechanical properties on a moving web. The properties include the extensional stiffness, S, in both the machine direction and cross machine direction, the anisotropy in the plane of the sheet, S_{MD}/S_{CD}, and the shear stiffness. The extensional stiffnesses may be used to estimate tensile strengths.

Introduction

Nearly all end use applications of paper or board leaving the mill involve strength specifications of one kind or another. These so-called strength parameters (e.g., burst, tensile, tear, edge crush, fold, etc.) are all destructive tests which, therefore, cannot be measured on-machine. This is unfortunate because much substandard paper or board can be produced before it is learned that the strength specification(s) is not met. Since there is no continuous record of product quality, tests performed on each sample of several square feet of material describe hundreds of thousands of square feet of product.

Although strength cannot be measured on-machine, it may be possible to measure certain other parameters on-machine which, independently or jointly, may correlate with the strength parameters. If this could be done, it would permit a continuous monitoring of product quality and perhaps provide control of the process as well. Either application would result in increased production by decreasing the quantity of substandard material.

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At present, there does not appear to be a single parameter that can be measured on-machine with sufficient accuracy and sensitivity to give the desired information. The joint use of two or more parameters in some strength algorithm would require the consolidation of a vast amount of existing theoretical and empirical technology. There is the possibility, however, that some parameter, heretofore not measured on-machine, could be an indicator of product quality or correlate with strength properties.

Since a great number of paper specifications involve mechanical parameters, it seems reasonable to attempt to measure some mechanical parameter on-machine. Elastic moduli describe the mechanical behavior of a material at low strains (where nondestructive tests must be performed). Therefore, the determination of elastic moduli on-machine, if it could be done, would be a step forward in characterizing the mechanical properties of the paper web. The elastic moduli are basic indicators of the mechanical state of the sheet and also correlate with some strength tests. For example, extensional stiffness (Young's modulus times caliper) has been shown to correlate with tensile strength when the level of refining, fiber length, and drying load are changed (1).

The velocity of ultrasound through paper is an intensive property that depends on a stiffness per unit mass. At low frequencies (<150 kHz), the velocity of symmetric plate waves propagating in the machine direction is given by (2),

$$V_{MD} = [E_{MD}/\rho(1 - \nu_{xy}\nu_{yx})]^{1/2} \tag{1}$$

where E_{MD} is Young's modulus* in the machine direction, ρ is the apparent density, and ν_{xy} and ν_{yx} are the in-plane Poisson ratios. The cross machine direction expression is

$$V_{CD} = [E_{CD}/\rho(1 - \nu_{xy}\nu_{yx})]^{1/2}. \qquad (2)$$

The in-plane Poisson ratios for machine made paper typically fall in the ranges 0.15 to 0.30 (ν_{xy}) and 0.30 to 0.45 (ν_{yx}) (3). This gives the term $1/(1 - \nu_{xy}\nu_{yx})$ a value usually between 1.0 and 1.1, and makes ρV^2 a good estimate of Young's modulus.** In an on-machine situation it would not be desirable to have to measure the apparent density, ρ. If V^2 is multiplied by the basis weight, a parameter already measured routinely on-machine, the result is an extensional stiffness, S (modulus times caliper). This is the parameter which correlates with tensile strength. Thus if one can measure both basis weight and longitudinal sound velocities in the MD and CD directions, the following quantities are obtained:

(1) V_{MD}^2 and V_{CD}^2, measures of the stiffness per unit mass in the MD and CD, respectively;

(2) S_{MD} and S_{CD}, extensional stiffnesses in the MD and CD directions, respectively, which correlate with tensile strengths in these directions; and,

(3) S_{MD}/S_{CD} (=R), a measure of the "squareness" or anisotropy in the sheet. Note from equations one and two that the ratio does not involve the approximation involving Poisson ratios noted earlier. Also, the anisotropy ratio R has been shown to correlate very well with similar ratios determined from stress-strain curves (3).

*Since paper is a viscoelastic material, and its elastic parameters are frequency dependent, Young's modulus in the above expressions will not equal those found by standard stress-strain measurement where more time is allowed for viscoelastic relaxation. The ultrasonically measured values are 20 to 40% greater than those taken from a stress-strain curve. The correlation between the two, however, is excellent as process variables are altered.

**Craver and Taylor (4,5) refer to this approximate Young's modulus as the "sonic modulus."

If shear velocities, V_S, are measured in either the MD or CD directions (the velocities are the same) one has:

(4) $V_S{}^2$, a measure of the shear stiffness per unit mass, and

(5) G_S (= $V_S{}^2$ x basis weight), the shear stiffness.

Stiffness values are quite sensitive to changes in refining, pressing, and drying conditions, and the measure of stiffness might be used to monitor one of these during the sheetmaking process. Elastic moduli, of course, are also quite sensitive to moisture content, and it would be necessary to have a simultaneous measure of moisture in order to correct the results for this effect. The anisotropy ratio, sensitive to fiber orientation and drying restraints, is quite insensitive to changing moisture (3).

Background

Laboratory investigations of ultrasonic wave propagation in paper have been carried out by a number of authors. Craver and Taylor (4,5) demonstrated that the sonic velocity was sensitive to refining, fiber orientation, wet pressing, and drying restraints. They found that for a given pulp the sonic velocity was related to the ultimate tensile strength over a beater run if the basis weight was held constant. Chatterjee (6) examined the correlations between sonic velocities and strength properties. Jackson and Gavelin (7) also studied the strength properties of kraft pulps using ultrasonic techniques. They showed that a high degree of correlationsexisted between anisotropy ratios determined ultrasonically and using mechanical tests. Jackson and Gavelin also noted that the nondestructive nature of ultrasonic testing might make it adaptable for on-machine use.

On-line ultrasonic measurements have been considered by a number of authors. Luukkala et al. (8) experimented with a noncontacting technique which yielded some interesting information concerning the nature of paper. The complicated relationships (9) that exist between the measured parameters and the elastic constants of paper, and the sensitivity of the method to temperature variations and air currents, however, make its application as an on-machine test method questionable. Papadakis (10) and Lu (11) both discussed potential methods for measuring elastic constants on-line, but apparently did not develop a usable on-line device.

Russian investigators have been active in applying ultrasonic methods for measurements of elastic and strength properties in paper. Sidorchenko and Fomenko (12) have reviewed much of this work and have developed an expression relating ultrasound propagation with the strength properties of paper. Unfortunately, all of the parameters needed in the expression are not available or are not determined with sufficient accuracy. Yastrebov and Kundzich (13) describe a paper strength meter which uses a time-of-flight principal. The transducers are positioned on a paper sample which is stationary during the actual measurement of ultrasound velocities. The device is not intended for use on-machine. Kazhis et al. (14) have described an ultrasonic apparatus for the measurement of paper strength on a moving web. This device also used a transmitter-receiver arrangement, although the transducers differ somewhat from those discussed previously. The transmitter uses a ceramic piezoelectric element mounted in a wheel which rolls along the surface of the web. The piezoelectric element is coupled to the outer rim of the wheel through a wedgelike tip of glass. When this contacts the web, the transducer is excited at 50 kHz, creating a mechanical disturbance in the web. The receiver element is noncontacting. It is mounted directly over a roll around which the paper wraps several degrees. At the roll, sound energy is radiated from the paper to the space above and is detected by a noncontacting piezoelectric receiver positioned there. This is said to reduce the amplitude of low frequency vibrations of the web which are a source of ultrasonic noise. The device is said to measure the ultrasonic velocity to 1% and the breaking length to within 6%.

On-line velocity measurements

Our initial attempts to build an on-line velocity sensor were centered around two noncontacting techniques. These included a scheme for electrostatically coupling ultrasonic energy in and out of the web and the method discussed by Luukkala. Our laboratory investigations (15) of these techniques produced results which were not promising enough to warrant further tests on-line. Thus we turned to a contacting scheme involving wheel transducers rolling along the surface of the sheet. Three such wheel transducers were envisioned, one serving as a transmitter and the others as receivers positioned so that MD and CD measurements could be made.

Our first attempts were made using sensor wheels from the Consolidated Bathurst Backtenders Friend™. These are designed to measure the hardness of a paper reel by measuring the waveform produced by a piezoelectric element which contacts the reel through an aluminum "button," once each revolution of the wheel. Although this application is quite different from our needs relative to a transmitter-receiver arrangement, Consolidated Bathurst was very kind in providing wheels on loan to us which we could modify to suit our needs. This was very advantageous for us, since the wheels already provided means for passing electrical signals into and out of the wheels and were proven in mill environments as far as the mechanical engineering aspects were concerned. In addition, Consolidated Bathurst personnel supplied us with a good deal of technical advice.

The Consolidated Bathurst wheels are 5 inches in diameter and 1.25 inches wide. The surface of the wheel which rolls along the reel is machined with a slightly convex surface. An aluminum button, 1.25 by 0.25 inches, is mounted on the wheel surface and is coupled to a piezoelectric transducer inside the wheel. As the wheel rotates and the button contacts the reel, the piezoelectric element produces an electrical pulse which is transmitted out of the wheel through mercury slip rings. This signal is analyzed to estimate the hardness of the reel.

In our application, the piezoelectric element in the transmitter must be excited electrically with a burst of sine waves, so that a mechanical disturbance is generated in the paper when the button contacts it. This mechanical disturbance propagates away from the wheel in all directions and is detected by the receiver wheels in which the piezoelectric elements transform the mechanical vibrations back into electrical pulses. With appropriate circuitry, the delay time for the mechanical disturbance to propagate in the paper between the transmitter and receiver(s) can be accurately measured (corrected for nonpaper delays). The ratio of separation distance to corrected delay time is the velocity of interest.

The propagation of ultrasound in the plane of the sheet involves particle motions (displacements) which are also largely in the plane of the sheet. This suggests that suitable designs would involve transducers which are polarized to displace parallel to the plane of the sheet. It was discovered, however, that the wheel sensors, as received, were quite efficient in exciting and detecting longitudinal (low frequency symmetric plate mode) waves, even though their piezoelectric elements are polarized perpendicular to the plane of the sheet.

Subsequent laboratory tests using pairs of transducers polarized either parallel or perpendicular to the plane of the sheet revealed that transducers polarized perpendicular to the plane of the paper were less efficient if acoustic coupling fluids were used but were more efficient than transducers polarized parallel to the plane of the paper in the absence of coupling fluids. Since it would be impossible to use coupling fluids in an on-machine application, the laboratory tests indicated that transducers polarized perpendicular to the plane of the web should be used.

Although the piezoelectric elements in the wheel sensors had the proper polarization, they were not intended to couple ultrasonic energy in and out of the web. It was thus necessary to redesign the transducer assembly in the wheels for our application. This involved isolating the active piezoelectric elements from the base of the wheel (to eliminate noise on the base from reaching the sensor), altering the coupling between the piezoelectric element and the aluminum "button," providing a quarter wavelength ballast opposite the button side to improve the response at 80 kHz, and using different piezoelectric elements.

The device for measuring on-machine ultrasonic velocities is shown schematically in Fig. 1. The wheel assembly shown in the lower left side of the figure has the following features. The wheels are shock mounted to isolate them from mechanical noise on the paper machine and are synchronized so that the transducer buttons on the transmitter and two receivers all contact the web at the same time. In operation, the moment of button-to-web contact is sensed by a position detector. This device is built from a Texas Instrument TIL139 source-sensor assembly, which contains a light emitting diode and a photodiode both mounted on one face of the module. When a reflective surface is placed in front of this face, the photodiode receives a signal from the light emitting diode. In operation, the position detector is mounted facing the receiver wheel.

A narrow piece of black tape is positioned on the wheel such that it absorbs the light from the position detector when the buttons are in contact with the web. The resultant drop in photodiode signal triggers the transmitter pulse and starts the counters which will monitor delay times in the machine and cross machine directions. In addition, for visual observation of the signals, the position detector can also trigger an oscilloscope.

[Fig. 1 here]

The transmitter is excited with a burst of sine waves generated by an Interstate F74 function generator, and amplified by an E. N. I. 240L power amplifier and pulse transformer. The transmitter frequency should be as high as possible to minimize effects of mechanical noise and improve resolution of the measured time differences, but must not exceed the point where the symmetric plate wave (S_o) mode becomes dispersive. On folding boxboard this occurs around 150 kHz (9). The piezoelectric element and aluminum button combination used in this work has a resonant frequency of about 80 kHz, and the transmitter is adjusted to this frequency.

The mechanical signal in the web propagates away from the transmitter in all directions. Both longitudinal and shear (transverse) particle motions occur. The signals detected by the receivers are small, and the resulting electrical signals must be amplified before being sent through the mercury slip rings. This is accomplished by small bandpass amplifiers mounted inside the rotating receiver wheels. The amplifiers are built around a single high speed National Semiconductor LM318H operational amplifier, having a gain of 20 dB. Power to the in-wheel amplifiers is supplied through mercury slip rings. The signals from the receiver wheels are further amplified by Panametrics 5050AE-160B ultrasonic preamplifiers, and then pass to a special electronic counter built in-house. In the latter the signals are filtered and fed to comparators which stop the counters when the signals are above a set level.

Each comparator is designed so that the received signal is retained only if the comparator is switched in a set time window. That is, the delay time between transmitted and received signal is displayed only if the comparator switches in this time window. This helps to eliminate erroneous delay times caused by extraneous signals. In addition, also to avoid the possibility of confusing noise for a valid signal, the time of arrival of the second pulse in the burst of sine waves is measured. If the time difference between the first and second pulses indicates that the signal is not near the frequency of the rf carrier, the output from the counter is not strobed into the display.

The measured delay times are displayed by four digit BCD light emitting diode displays which register the delay times to the nearest tenth of a microsecond. The delay times as measured include delays through the electronics, piezoelectric elements, and buttons, as well as the paper. The nonpaper delays can be determined several different ways and can be handled in the electronics by presetting the counters to negative numbers. The velocities of ultrasound in the MD and CD are then calculated by dividing the paper delay times into the respective separation distances in the two directions.

The system, as described, is quite capable of making measurements on static webs and thus easily provides a means of optimizing the system performance for a given paper. The rf frequency, button location, wheel synchronization, and initial phase of the rf pulse are individually adjusted for best receiver signal. On the moving web, the contact between the wheels and paper is important. Nonpaper delay times can be measured by placing the transmitter and receiver buttons in contact, by using a "standard reference" material in place of the paper, or by measuring the delay times at several different separation distances. In each case the paper and nonpaper delay times can be separated.

In the present system, the longitudinal wave transit time is measured in the machine direction, whereas the shear wave transit time is simultaneously measured in the cross machine direction. This occurs because of the internal design and the particular configuration used for the sensor wheels. At present, R is estimated from the MD extensional stiffness and the CD shear stiffness. It should be relatively simple to redesign the CD sensor to detect the longitudinal wave, permitting a direct measure of R.

All measurements on moving webs have thus far been made on belts mounted on the continuous web strainer at IPC. Ultrasound velocities in linerboard samples have been measured at web speeds in excess of 1500 fpm, and have been shown to be independent of web speed (as expected). At higher web speeds the signal to noise ratio decreases and the ultrasonic coupling between button and web becomes rather variable. Efforts are currently underway to minimize these difficulties, and involve changes in both mechanical and electrical designs.

Even though the digital output of the device described becomes hard to stabilize at the highest web speeds, the received signal is easily detectable on an oscilloscope, and an operator can quite easily read the delay time from the oscilloscope trace. Uncorrected delay times are of the order of 80 microseconds (MD) and 160 microseconds (CD) for a linerboard sample. Typical variations in transit time measurements due to web inhomogeneity (in the belts) and coupling instabilities are about one microsecond.

Calculable parameters

Typical MD and CD velocities for linerboard are ~3.5×10^3 m/sec and 2.0×10^3 m/sec, respectively. These values are considerably larger than usual web velocities, e.g., 2000 fpm = 10.16 m/sec, so that web speed effects need not be considered. As noted earlier, if the square of the velocity is multiplied by basis weight, the extensional stiffness is found. With the present device, assuming an accuracy in the digital measurements of one microsecond out of 100 microseconds, the error in the stiffness values is about 2% (not taking into account any errors in basis weight determination). The uncertainty is less if transit times are measured using an oscilloscope and counter [see Reference (16)]. The anisotropy ratio, R, is the ratio of the MD stiffness to CD stiffness, and thus is independent of basis weight. The anisotropy in machine-made paper is a result of fiber orientation effects and differences in drying restraints in the two directions as it passes through the driers. Thus the anisotropy ratio could be an effective indicator of changes in these two factors. For example, the value of R may be useful in controlling jet-wire speed ratios on the paper machine.

Figure 2 shows the relationship between ultrasonic extensional stiffness and tensile strength for handsheets made from the same furnish, and having the same basis weight, but differing in wet pressing and refining treatments. (The measurements were made on static samples.) It is quite clear that on-line measurements of MD and CD stiffness should be good indicators of MD and CD tensile strength, respectively, as determined (destructively) off-machine.

[Fig. 2 here]

Acknowledgments

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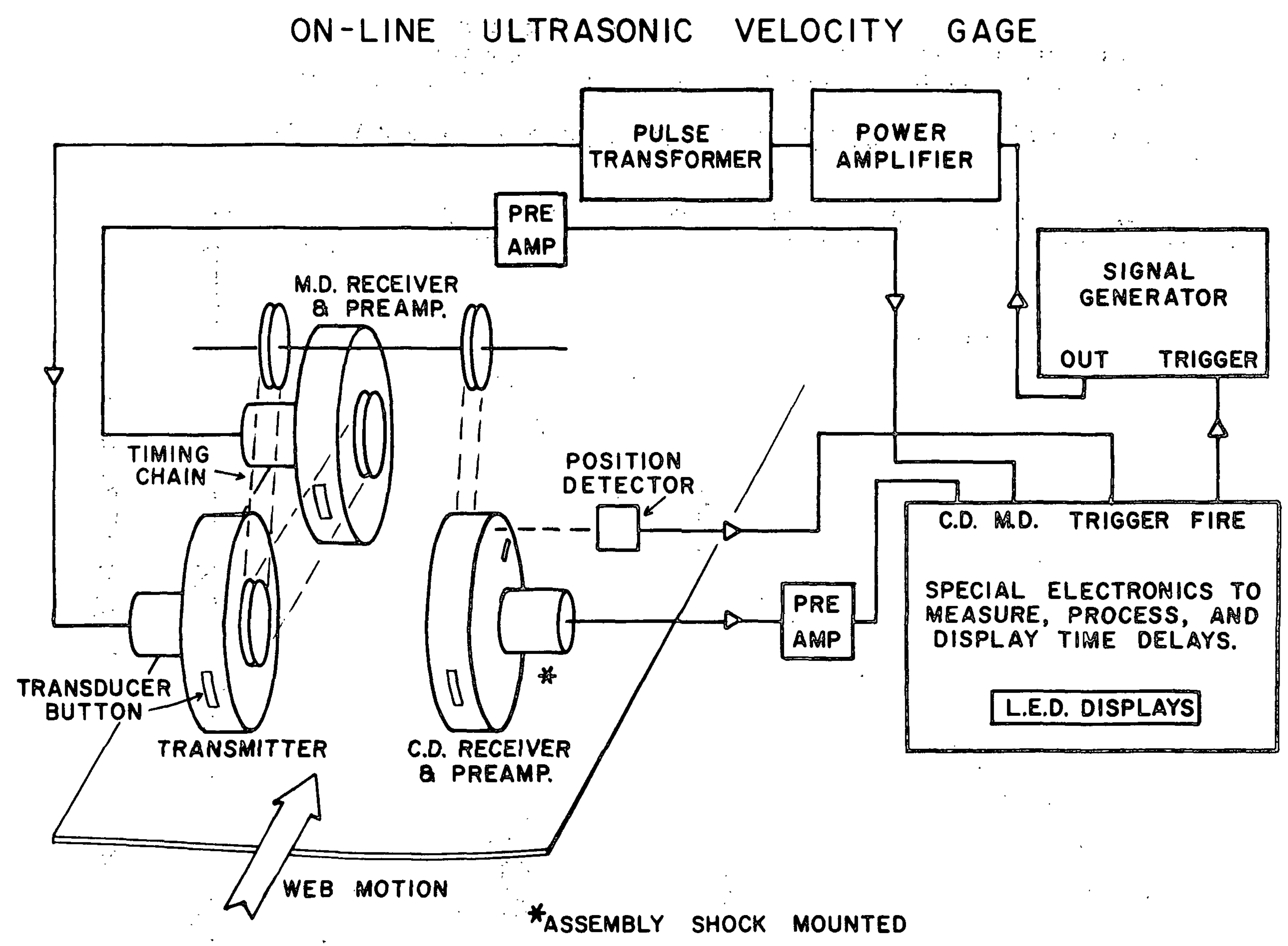

Figure 1. Schematic of an on-line ultrasonic velocity gage

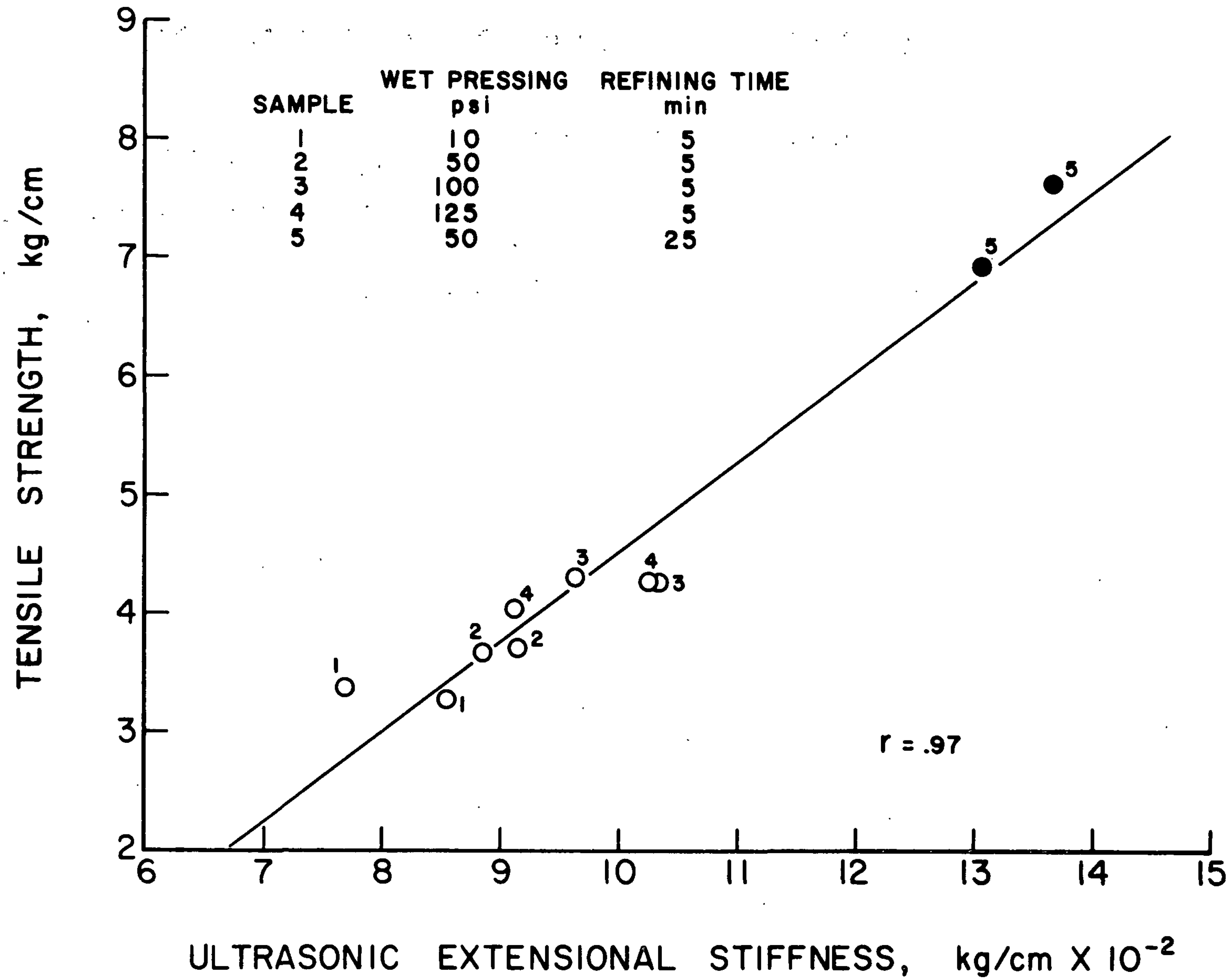

Figure 2. Correlation of ultrasonic extensional stiffness with tensile strength. Unbleached kraft handsheets with a nominal basis weight of 125 m/m^2