COMPRESSIVE MODULUS MEASUREMENT TECHNIQUES

by

J. D. Pfeiffer
JDP Innovations
CANADA

ABSTRACT

The compression testing of stacks of sheet materials is done to learn the behavior of the group of sheets, a behavior that is quite different from that of a solid, or even one single thick sheet of the same material. Many interfaces are present at the sheet contact, consisting of soft fibers, asperities, or minor surface protrusions, and these cooperate to make the stress-strain relationship of the package nonlinear. Reasons for doing the testing are presented, with models for estimating the pressure versus strain curves, and implications for roll structure prediction based upon these models. The concept of strain loss in compression is reintroduced, and techniques are presented for improving curve-fitting when strain loss exists. A list of alternative ways for evaluating wound roll structure is given, with comments on the relative merits of these methods.

INTRODUCTION

Web material wound into roll form has properties in the tangential direction, around the circumference of the roll, that are different from those in the radial or perpendicular direction. In the language of mechanics and mathematics, this is known as anisotropy. Many naturally occurring materials are anisotropic, for example, wood. In layered materials, there is every reason to suspect that the fundamental material properties will be different in every coordinate direction. One of these directions is in the direction of forming, rolling or extruding the material. Another direction is perpendicular to this, staying within the plane of the web. Depending upon the method of manufacture of the layers, the modulus of elasticity to extend the material in each of these two directions might be quite different.

A different story exists in the direction perpendicular to the sheets, where measurements must travel through the interfaces between multiple numbers of sheets. At these interfaces, significant displacements happen at low pressures, as fibers and asperities are brought into intimate contact. As the individual sheets are brought more closely toward each other, the pressure resisting this approach mounts, slowly at first and then increasing ever faster, as the number of fibers in contact increases, or the distance between neighboring points of contact becomes much shorter. The physical reasons for the stress-strain behavior of sheet materials to be nonlinear has been studied by a number of researchers (1,2). In almost all materials, closer approach will produce increased stiffness of resistance to motion. Either the unsupported bending length of fibers decreases as more fibers contact each other, or in non-fibrous materials, the distance between asperity contact points shows a rapid decrease as the number of points in contact increases. This causes the sheet support to go from light when there is sparse contact, to rigid support when the contacting points move close together.

The stress-strain behavior of a stack of sheet material is measured when it is necessary to determine the compressive modulus of the material. This corresponds to measurement in the radial direction in a wound roll, the direction perpendicular to the surface of the sheets. As we have seen, it will most likely be a nonlinear function of applied pressure. The stress-strain relationship measured in the circumferential direction around the roll, is normally sufficiently linear to assign a constant value to the tensile modulus, independent of the level of stress. In extensible materials which contain crepe induced during their manufacture, such as masking tape, facial tissue, and extensible packaging materials, the modulus may indeed be load-dependent, but this is the exception rather than the rule.

WHY MEASURE A MODULUS?

It is easy to understand why knowledge of the tensile modulus is important. It measures the stretchability of the product, and if the ultimate strength of the product is known, it provides the information on how much it will stretch before it breaks. An accurate knowledge of the tensile modulus is also necessary when predicting or computing the structure of a wound roll of material. The amount of energy put into elongating a given volume of web material translates into the degree of tightening or firmness of the rolled product. When the modulus is low, the tensioning force is exerted through a greater distance, providing more work per unit volume and storing more energy in the roll structure. If the tensile stress imparted to the material is σ_t, causing a strain or extension of ϵ_t, then the work done per unit volume is the area under the graph of σ versus ϵ. This equals $\frac{1}{2}\,\sigma\cdot\epsilon$ for a linear material. Incorporating the tensile modulus E_t, which relates the proportionality between stress and strain, the slope of the curve, we have

$$U = \tfrac{1}{2}\,\sigma_t^2/E_t \qquad (1)$$

where U is the unit energy per cubic volume. This formula shows why there is more energy stored in a low modulus material since E_t appears in the denominator.

Enter the Compressive Modulus

In a wound roll of material there will be high amounts of residual tension in the outer wraps. The pressure between layers will increase when following along a radius into the roll body due to the cumulative effect of the tensile wraps. Deeper in the inner roll body, in terms of first-order effects, the energy that was initially in the form of tensile straining is converted in whole or in part to the energy of radial compression of a stack of the material. This is where the compressive, or radial, modulus enters the picture. We need to measure a stack of piled material to find the energy necessary to compress it to the same amount of energy per cubic volume that was put into tensile straining. Since the relationship of stress to strain when compressing sheets is nonlinear, we must integrate the area under the stress-strain curve to find an area which is equal to the amount of stored energy. Once this is found, we have an estimate for the amount of layer-to-layer pressure at that point within the roll, and the amount of radial strain that exists locally. Radial straining causes a proportionate shrinkage of the radius, and this is why the residual tension decreases when travelling inward along a radius of the wound roll.

Although the discussion in the paragraph above tends to oversimplify the complicated solution to the problem of calculating roll structure, it gives an intuitive feeling for understanding the relationship between winding tension and tightening of the roll by developing internal pressure. The next step is to study ways of obtaining the stress-strain curve in compression for various materials. The actual curve (Fig. 1) has two parts, one is the path along the curve followed when the pressure or strain is increasing on the pile, and the other is obtained when the pressure or strain is relaxed from maximum back toward zero. The computer programs for roll structure determination do not normally allow for both curves to form part of the input data for the calculation. It is up to the user to select whether the ascending pressure curve or the descending pressure curve is more appropriate. Most of the time, the ascending pressure curve is utilized, as this models the behavior of the web material when it first goes onto the roll, instead of the behavior when it is unwound.

MODELS FOR REPRESENTING THE COMPRESSIVE MODULUS

A mathematical model for one of the curves representing compressive stress-strain behavior is more useful than using all of the data points taken during a test of sheet material between test machine dies. The equation form used for the model may be dictated by the input requirements for the roll structure modelling program used, but in the two most popular forms for the modulus, conversion between the models is possible. The Hakiel polynomial (3) consists of coefficients which fit the modulus or slope relationship using a power series on the pressure between layers, σ_r. Although the actual stress carries a negative sign because it is compressive, not tensile, we normally refer to it as a positive quantity as in the series below:

$$E_r = C0 + C1*\sigma + C2*\sigma^2 + C3*\sigma^3 + C4*\sigma^4 + ... \qquad (2)$$

It is seldom necessary to use terms beyond C2 to describing the behavior, as little additional knowledge of roll structure is gained by including the third, fourth, and higher order terms.

The Pfeiffer model (4,5) is based on a fit to the stress-strain curve instead of the modulus. From this the compressive modulus is determined by differentiation.

$$\sigma_r = -K1 + K1*EXP(K2*\epsilon_r) \qquad (3)$$

$$E_r = d\sigma_r/d\epsilon_r = K1*K2*EXP(K2*\epsilon_r) = K1*K2 + \sigma_r*K2 \qquad (4)$$

Comparing this result to the Hakiel polynomial (2), it is apparent that in the Pfeiffer model, K1*K2 is equivalent to Hakiel's C0, and K2 is the same as C1. These two terms indicate a radial modulus E_r that is proportional to pressure, offset by the constant term C0, or K1*K2. As mentioned before, there are two sets of coefficients, one for ascending pressure and the other for descending pressure, and the user should determine which is to be used.

Another expression was suggested by Pfeiffer (6) with the intent of finding a closer fit to experimental data:

$$\sigma_r = -K1 + K1*EXP(K2*\epsilon_r)+K3*\epsilon_r \qquad (5)$$

Its does improve the fit to data, but it introduces unnecessary complications, such as more terms in the modulus expression, and the need to back-solve iteratively when the pressure is known and the strain is to be found for that pressure. Equation (3) may be solved for strain as a function of pressure by moving the -K1 term to the other side, and taking logarithms of both sides. In this discussion, an alternate way of finding a good fit to experimental data will be shown, while preserving the simplicity of equations (3) and (4).

$$E_r = d\sigma_r/d\epsilon_r = K1*K2*EXP(K2*\epsilon_r) + K3 \qquad \text{[for Eq. (5) above]}$$

$$= K1*K2 + \sigma_r*K2 - K2*K3*\epsilon_r + K3 \qquad (6)$$

This complicated expression may be used in roll structure models, but caution must be exercised as certain values of K3 may cause the modulus to turn negative in the low pressure ranges. This is shown in Fig. 3, where the decreasing pressure curve has a long span of near-zero pressure. The only way for the coefficients to fit the data in this area was to arrive at a large negative value for K3. This caused the pressure curve to swing below zero, which in turn creates a negative modulus near the origin.

MEASUREMENT TECHNIQUES

Now that we know what we are after, we must go to the laboratory to measure the actual stress-strain curve(s) for the material in question. This is where it gets tricky and finicky. There are a number of concerns. What test machine is to be used, what area of compression dies, what pile height, should the edges of the pile be trimmed, and what test cycle time is to be used? At each decision point there are several considerations. If a constant strain rate type test machine is to be used, such as an Instron laboratory machine with geared lead screw drive moving the dies together, there may be a problem in picking the number of inches per minute travel that will give a reasonable test cycle duration. If the dies approach each other slowly, the pressure may increase at a suitable rate during the initial compression of the pile, but as the slope of the compression curve increases, the pressure may shoot up rapidly, causing problems of possible pressure overshoot and even damage to the force-measuring load cell. In this type of tester, the strain is measured by the position of the crossheads carrying the dies. The load cell is usually contained between the crossheads as well, so that the deflection measured should be compensated by subtracting any deflection occurring within the load cell itself. If the deflection rating of the load cell is not known, it may be measured on the test machine. But be very, very cautious when doing this, as many good load cells have been ruined by technicians unaware of the risk of bringing the crossheads together when nothing but the load cell occupies the space!

In a test machine that is used for a wide variety of measurements, each test leaves the machine in a different configuration. There might be tensile testing on one day, adhesive peel strength testing on another day, and so on. When the machine is reconfigured for compression testing, it is essential to verify that the setup is made as close as possible to one of a previous day, or else the results will not be repeatable. The parallelism of the dies is one aspect that is often overlooked. Hydraulically-operated testing machines such as MTS test machines can be configured to apply load to the specimen under programmed control though a load-sensing arrangement, with feedback to a hydraulic servo valve controlling the oil flow into the test cylinders. Errors may be introduced by this type of control system if any instability, hunting, or overshoot occurs, as the dies could have extra oscillatory motion imparted to them, so that the compression curve is traced out by a series of small hysteresis loops which dance around the desired curve, but do not follow it exactly. The arrangement for measuring the position of the dies, which will be the basis from which the strain data is obtained, should have the necessary resolution and repeatability to obtain valid data. In many cases the load capacity of the test machine is far in excess of the few hundred pounds required to load the specimen, making it difficult to measure small displacements and control small forces on such a large machine.

Where die area and specimen height are concerned, the user is at liberty to set his or her own standards. The force will be divided by the area to normalize it to kilopascal or psi units, so the area used will be factored out. The strain will be calculated by dividing any incremental displacement of the dies by the original pile height at zero strain (Note: this is not easy to measure) resulting in non-dimensional strain. Sampling effects may introduce errors if only a square centimeter or so is used as the die area. What is seen under one localized area of the material may be different from adjacent areas on the same web, if the die area used is too small. We recommend using a die area of 4 square inches (2580.6 mm^2) with circular dies and an initial pile height of 1 inch (25.4 mm). This choice was set arbitrarily thirty years ago by what was currently available in the lab, and with the realization that a very tall pile height was basically unstable and hard to handle. At the same time, we established a recommended cycle time of 60 seconds (1 minute) to go from zero pressure to full load, a 1-minute rest at full load, and a 1-minute time period for the relaxation of load back to zero. Although this is only a suggested time base, it does allow comparison of data between various labs, and has some relation to the amount of time material in the roll spends in lower pressure zones before it reaches higher pressures during winding.

For materials that exhibit a low Poisson ratio when compressed (their sideways growth is barely or not at all measurable), it is not necessary to trim the edges of the pile. The material may be allowed to extend outside the area of the dies. There may be some fringing of the compressive forces, but this will not be serious when the Poisson ratio is low. Most paper and plastic film materials exhibit this sort of behavior. With materials that tend to go solid at the upper pressure levels of the test, such as sheet rubber, very soft plastic films, films containing soft coatings, or films that are wound extremely tightly on the roll, this may not be true. If that is suspected, the Poisson ratio may be measured during the test by trimming opposing edges of the pile and cementing small metallic reflectors to the pile sides. The displacement or growth of the pile in width as the pressure is applied may be recorded by focusing infrared displacement transducers on the reflectors and differencing their outputs.

DETERMINATION OF THE FIRST CONTACT WITH THE PILE

The first contact of the dies with the pile or stack of sheet material will set the initial height of the stack H_0. The strain ratios will be calculated by dividing deflections measured from the point of contact by H_0. An error of a percent or two in estimating original pile height will not greatly affect the value of strain at maximum deflection, as the difference between first contact and maximum deflection of the stack will be a large number. However, the distance between the point representing first contact, and the point representing the next data point at low pressure will reflect strongly any error in the stack original height. These two displacement values will determine the slope of the modulus curve between them. If they are too close together, the modulus will appear to be too high, and if they are far apart, a very low modulus will be obtained. This distance also represents a strain loss on compression in the material, which will not be recovered due to the hysteresis in the stress-strain curve. This initial strain loss plays a strong role in winding rolls with no rolling nip contact where the web enters the roll, or very light nip force. Under these circumstances, it causes a large percentage of the web's free-span tension to be lost without chance of recovery (7,8). This causes the roll to be wound much more loosely than the roll structure calculation would predict based on full web tension going into the roll.

Estimating the point of first contact of the dies with a stack of material under test in a fixed strain rate test machine is tedious, requiring that the dies should be brought together slowly under manual control, which is never quite fine enough to be satisfactory in these machines. As can happen when calibrating the load cell alone, the dies may come together too fast or travel too far, putting excessive initial stress on the stack, requiring it to be replaced by a fresh sample. The alternative is to allow the machine to drive the dies together at an extremely slow strain rate, and this requires great patience to stop the feed at exactly the right point. In one model of table top compression test machine, where the dies are moved by a low-friction bellows-type air cylinder, it is possible to manually adjust the initial air pressure until the moving die just begins to move upward. Then by gently pushing the stack laterally, the onset of first contact can be sensed at very low force values. Both the value of displacement and the initial force, taken as a reference value, are saved when a push-button is pressed to start the test cycle.

FITTING STRESS-STRAIN DATA TO THE MODEL

Once a collection of data points has been acquired by a computer connected to the test machine, the next step is to use a statistical program to map the data by regression techniques into one of the models, Equations (2), (3), or (5). Several computer programs are available to produce the unknown coefficients, C0, C1, C2..., or K1, K2 (and K3) from the data. The ability to fit a curve passing as close as possible to the original data points is very good, typically with rms errors less than one percent if the original data is free from spurious noise or vibration effects.

Fitting K1 and K2 alone to the experimental data, as shown in Figure 2, usually results in a curve that passes above the data points at the start and finish points of the test, but below the data points in the mid range. When K3 is added as in Equation (5), the fit improves greatly, but problems occur between the origin and the first data point, where either the pressure or E_r or both may become negative, Figure 3.

A new technique has been developed to fit K1 and K2 to the data, beginning at the higher pressure and strain values and working backward, to avoid the influence of the strain loss between the point of initial contact and points of moderate pressure. This fit produces the curves of Fig. 4, which match to the experimental data points as well or better than Equation (5) can do. The point where the calculated pressure is zero occurs when EXP(K2*ϵ_r) equals one, in other words, at zero strain. This does not match up with the point of initial contact, as shown in Fig. 4. The difference between the strain at the reported initial point of contact and the point where the equation predicts zero pressure is the strain loss, the amount of initial travel necessary to seat the asperities into opposing contact, or to begin to flatten the initial stick-out of fibers in a fibrous web. Since this curve fits the experimental data well and has the right slope in the upper regions of the graph, it may be used to obtain the radial modulus by differentiation (Eq. 4) and thereby obtain the Hakiel coefficients C0 and C1. For quality control purposes is recommended that strain loss values should be recorded together with K1 and K2. The strain loss numbers are required as well for estimating the hysteresis loss of the compression cycle, which is the area enclosed by the up- and down- curves divided by area under the ascending pressure curve. Another advantage afforded by the strain loss measurement technique is that it gives more dependable numbers for K1 and K2 for production control purposes. The procedures for calculating K1 and K2 based on Fig's. 2 and 3 produce errors in K1 and K2 due to errors in reporting the strain at initial contact (9).

OTHER MEANS OF DETERMINING ROLL STRUCTURE

To prove the accuracy of roll structure models, it is necessary to measure the interlayer pressure, residual tension, hardness, or some other quantity that will compare actual roll structure to predicted roll structure. A number of techniques have been employed in the past. They range from completely non-destructive to fully destructive.

Cameron Gap Test -- A roll is supported on its side by gravity weight. After cutting through a number of wraps to a point where the next measurement is to be taken, a single ply is cut carefully in a line across the roll face, and that layer is allowed to spring open under residual tension. The two ends of the cut web are brought together, and the gap distance, measured between the ends, when divided by the circumference, results in a reading for residual tensile strain at the outer wrap for that radius. To obtain points for all radii, the roll must be slabbed down all the way to the core, taking readings periodically. The test is destructive.

Smith Needle -- A spring-loaded plunger with a polished needle on the end is attached to a dial indicator gage. The needle is pushed into the roll outer face to a fixed depth, while trying to go between the layers rather than pierce or cut them with the point. A number indicating relative resistance to the thrust on the needle is read from the dial indicator and plotted. These numbers are converted to pressure readings by a chart calibrated by pushing the needle into rectangular stacks of material which have been compressed to a known pressure. The test is labelled destructive on delicate webs, but the roll could be cut to a narrow width to eliminate the possible damaged edge. If the roll is not uniform in hardness across the face, the results are not representative of the average roll condition.

Sonic Velocity Testing -- In 1966 a narrow roll was supported on a bar passing through the core, with a transducer between the bar and the inside of the core (10). The time delay for impulses sent from the transducer to arrive at various points along the radius were measured and compared to a calibration curve made during a stack test of the same material at known pressures. Another testing device made by Ron Swanson (11) was described at IWEB1.

Pull tabs and force-sensitive resistors -- Typically employed at lower winding speeds under laboratory conditions, these devices must be inserted into the roll while it is turning. To avoid risk to life and limb, automatic feeding and inserting devices are sometimes employed. The resistance to pulling out a tab from the side of a wound roll is an indication of interlayer pressure. Force-sensitive resistors (12) change their resistance values as a function of pressure. They are convenient to use, requiring only an ohmmeter to read their resistance, however special techniques are required for calibration to obtain accuracy and repeatability. Their stability requires that readings should be taken at predetermined times, and temperature and weather changes are additional factors affecting stability.

WIT-WOT machine -- The initials stand for wound-in tension, wound-off tension. At one or more locations in the U.S. rolls can be analyzed by unwinding them with the outer wrap travelling around a measuring roll and then re-wrapping the unwinding roll for half of a turn. The tension in the measured loop reflects the residual tension as it comes to the surface of the unwinding roll (13). Recent improvements to these machines include belts to support the web in contact with the roll, so air-flotation of the web does not cause slippage.

Roll density monitors -- Once a laboratory curiosity, these digital on-line gages can be included or retrofitted on most paper machinery winders. Improvements since the early developments by Leif Eriksson and others (14) have resulted in readings which are not confused by caliper changes in the product (15). The readout shows roll density in absolute units on a monitor screen plotted against product roll diameter. Applications to film winding are sometimes hampered by not being able to obtain core rotation digital signals, or a digital encoder cannot be mounted to measure the web velocity, because traction between webs and carrying rolls may be intermittent. One of the inputs for calculating absolute density is the basis weight of the product. When this information is not available on a continuous basis, calibration may be maintained by spot checks of the product's shipping weight and volume.

CONCLUSIONS

Technique is everything in maintaining accuracy and reproducibility in measurements. Some techniques apply to the mode of operating laboratory test machines, and it is equally important to understand what is happening in the material itself and to use proper techniques to fit the data to mathematical models. Repeatable measurements are absolutely necessary if statistical quality control methods are being used in manufacture. When compressibility measurements and tensile modulus parameters are used as inputs to roll structure models, the simulation is only as good as verification using actual rolls will demonstrate. Some of the most commonly used methods for evaluating the structure of wound rolls have been presented. These can not only tell that the computer models are working well, but can give information on the amount of tension that is actually being received by the layers of the roll as they are wound. The input data for wound-in tension as a function of radius is one of the most difficult pieces of information to obtain when running a roll structure modelling program.

REFERENCES

1. Elias, T.C., "Investigation of the Compression Response of Ideal Unbonded Fibrous Structures", TAPPI J., Vol. 50 No. 3, Mar 1967, pp. 125-132.

2. Forrest, A.W.Jr., "A Mathematical and Experimental Investigation of the Stack Compression of Films", Proceedings of the Second International Conference on Web Handling, OSU, June, 1993, pp. 191-206.

3. Hakiel, Z. "Nonlinear Model for Wound Roll Stresses", TAPPI J., Vol. 70 No. 5, May 1987, pp. 113-117.

4. Pfeiffer, J.D., "Mechanics of a Rolling Nip on Paper Webs", TAPPI J., Vol. 51, No. 8, Aug 1968, pp. 77A-85A.

5. Pfeiffer, J.D., "Measurement of the K2 Factor for Paper", TAPPI J., Vol. 64, No. 4, Apr 1981, pp. 105-106.

6. Pfeiffer, J.D., "Surface Winding to Overcome the Strain Deficiency", TAPPI J., Vol. 73 No. 10, Oct 1990, pp. 247-249.

7. Good, J. K., Pfeiffer, J.D., "Tension Losses during Centerwinding", TAPPI 1992 Finishing and Converting Conference Proceedings", Oct 1992, pp. 297-306.

8. Good, J.K., Pfeiffer, J.D., Giachetto, R.M., "Losses in Wound-On-Tension in the Centerwinding of Rolls", Proceedings of the ASME, Winter Annual Meeting, AMD Vol 149, Nov 1992.

9. Pfeiffer, J.D., "Practical Applications of the Compressibilty Equation Suggest Simplification", TAPPI 1998 Finishing and Converting Conference Proceedings", Oct 1998, pp. 125-128.

10. Pfeiffer, J.D., "Internal Pressures in a Wound Roll of Paper", TAPPI J., Vol. 49, No. 8, Aug 1966, pp. 342-347.

11. Swanson, R.P., "Determination of Wound Roll Structure Using Acoustic Time of Flight Measurements", Proceedings of the First International Conference on Web Handling, OSU, May 1991, pp. 57-67.

12. Good, J.K., Fikes, M.W.R., "Using Force-Sensitive Resistors to Measure Radial Pressure in Wound Rolls, Proceedings of the First International Conference on Web Handling, OSU, May 1991, pp. 32-39.

13. Pfeiffer "Wound-off Tension Measurement in Paper Rolls", TAPPI J., Vol. 60, No. 3, Mar 1977, pp. 106-108.

14. Eriksson, L.G., Lydic, C., Viglund, J.A., "Measurement of Paper Roll Density during Winding", TAPPI J., Vol. 66, No. 1, Jan 1983, pp. 63-66.

15. Baum, S.A., Roissum, D.R., " Caliper Effects on Wound Roll Density", TAPPI 1991 Finishing and Converting Conference Proceedings, Oct 1991, pp. 129-137.

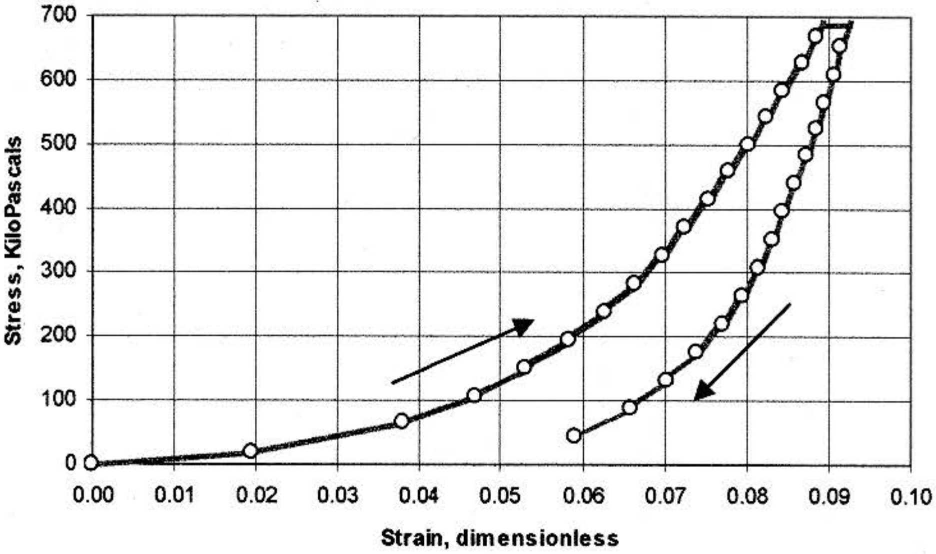

Fig. 1 Compression curve for a stack of 99 µm bond paper, 76 g/m² basis weight. Loaded to 689 kPa in one minute, held there for one minute, then reduced in pressure during one minute. Arrows show the direction of loading. Straight lines connect the data points.

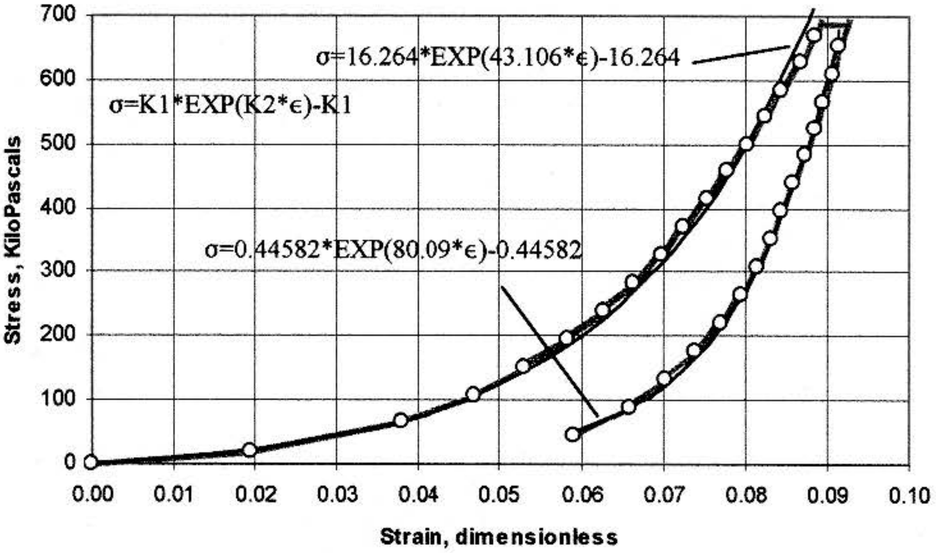

Fig. 2 Exponential compressibility equation (3) fit to the data points for ascending and descending pressure. Using only K1 and K2causes underestimation of the mid-range data points, and overestimation at the top, as shown. Rms error of the fit to the top curve = 4.80%, for the decreasing pressure curve 2.92%.

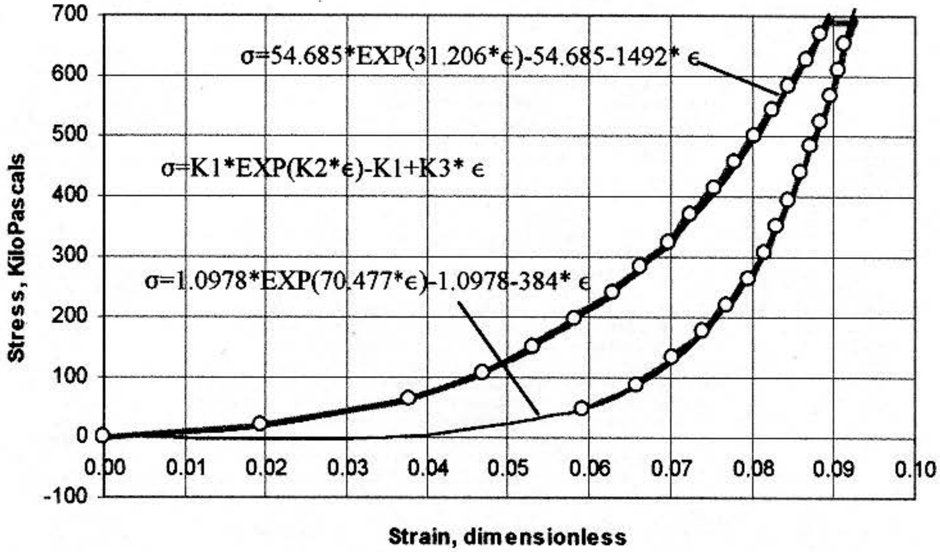

Fig. 3 Addition of the K3 term using Eq. (5) improves the fit to the data, but causes the estimation to be slightly negative near the origin, and the expression for the radial modulus becomes more complicated (Equation 6.) The ascending pressure curve now has rms error of 1.22%; the descending pressure curve has 0.99% error.

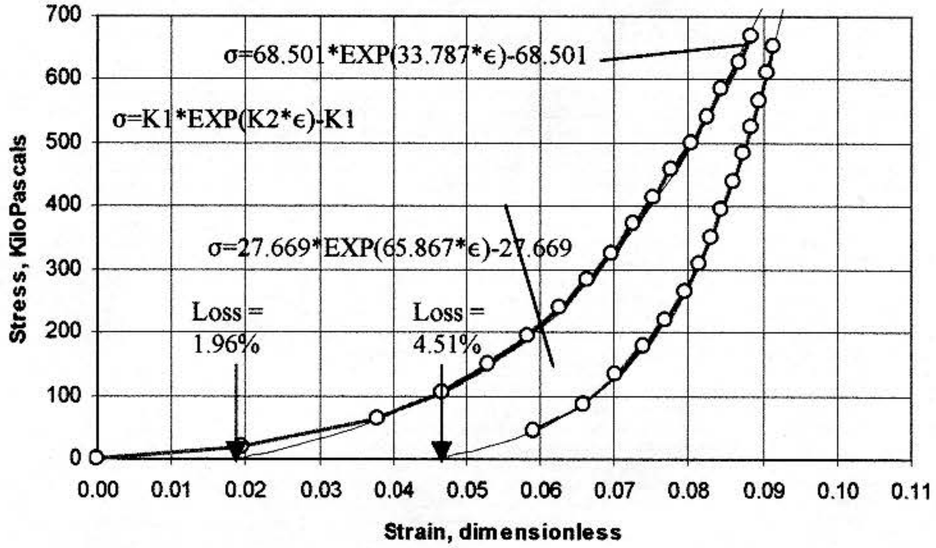

Fig. 4 Strain loss method allows fitting the curves with Equation (3). To emphasize the top portion of the curve, a few of the low-pressure data points are omitted. Then the original stack height H_0 is varied to optimize the fit. The ascending pressure curve rms error is 1.22% as above, but the descending curve has 0.73% rms error.

J. D. Pfeiffer
Compressive Modulus Measurement Techniques
6/7/99 Session 1 11:00 – 11:25 a.m.

Comment - Al Forrest, DuPont
We use just K2 and K1. With enough K2 measurements one begins to get a relative "feel" for the compressibility of various webs. The slight loss of accuracy that you get is over whelmed by the simplicity.

Comment – Jan Erik Olsen, PFI
You mentioned that when you are measuring the strain-stress curve the test period is on the order of one minute. When you are winding the cycle occurs much faster.

Answer – J. D. Pfeiffer, JDP Innovations
That flash through the first nip is on the order of milliseconds that is superimposed every time around. You could measure the compression with a short time impulse, but you have to make a compromise or you will get a wild amount of hysteresis. It is better to do it over a longer time period. If your application says it is wise to do a rapid test application, this could be useful to your studies.