Acoustic and optical measurements of paper under strain

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ABSTRACT: Deformation of handsheets under tensile load was investigated by simultaneously measuring acoustic emissions and optical reflectance. Handsheets were made from bleached softwood kraft pulp at three levels of laboratory beating. Significant differences were observed in the behavior of acoustic and optical properties during straining. The gradual increase in optical reflectance with increasing irreversible elongation suggests that the optical contact between fibers is gradually disrupted under load. The acoustic data, on the other hand, suggest that disruption of fiber-to-fiber bonds increases exponentially with increasing elongation.

KEYWORDS: Acoustic measurement, breaking, coefficients, deformation, elongation, fiber bonding, hand sheets, measurement, mechanical properties, optical measurement, optical properties, optical scattering, paper properties, paper sheets, properties, reflectance, scattering, strains, tensile properties

The use of an acoustic emission (AE) test method to investigate the fracture of fiber–fiber bonds and the deformation of paper under tensile load has been demonstrated in previous studies (*1, 2*). These studies showed that AE is a sound emission caused by microfailure, with an increase in AE events implying the breakage of fiber–fiber bonds and/or fiber failure during tensile deformation (*3*). The scattering coefficient for a paper sheet also increases during tensile straining, and this increase has been regarded as evidence of bond breakage (*4*). The work of Nordman clearly demonstrates the increase in opacity that occurs during cyclic straining–relaxation of a paper sheet (*5, 6*). However, there is considerable controversy about whether the increase in opacity is attributable to the breakage of bonds between fibers.

In this work, optical reflectance, AE event count, and tensile load were measured simultaneously in handsheets undergoing both single tensile straining as well as cyclic straining and relaxation. The primary objective was to understand why sheet opacity increases during tensile straining. The experimental results also provided some insight into the structural change that occurs in a paper sheet under tension.

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Experimental

Materials

A commercial bleached softwood kraft pulp was beaten to various degrees in a PFI mill under standard conditions. Handsheets were made using the method described in TAPPI T-205.

Instrumentation

The configuration of the instruments used for simultaneous measurement of load, AE, and optical reflectance is shown in **Fig. 1.**

Tensile testing. A paper specimen, cut to 15 mm in width by 120 mm in length, was strained in tensile mode using an Instron-type machine (Shimadzu Autograph AGS-100) with a span of 100 mm. Crosshead speed was 2 mm/min.

Acoustic measurement. The AE occurring in the paper specimen was detected with a sensor that was attached to the clamp of the Autograph with a quick-setting adhesive. The signal from the AE sensor was amplified by 40 dB and filtered through a high-pass filter with a low-frequency cutoff of 50 kHz to eliminate low-frequency noise (*1*). The AE signal was further amplified using a logarithmic amplifier (*3*).

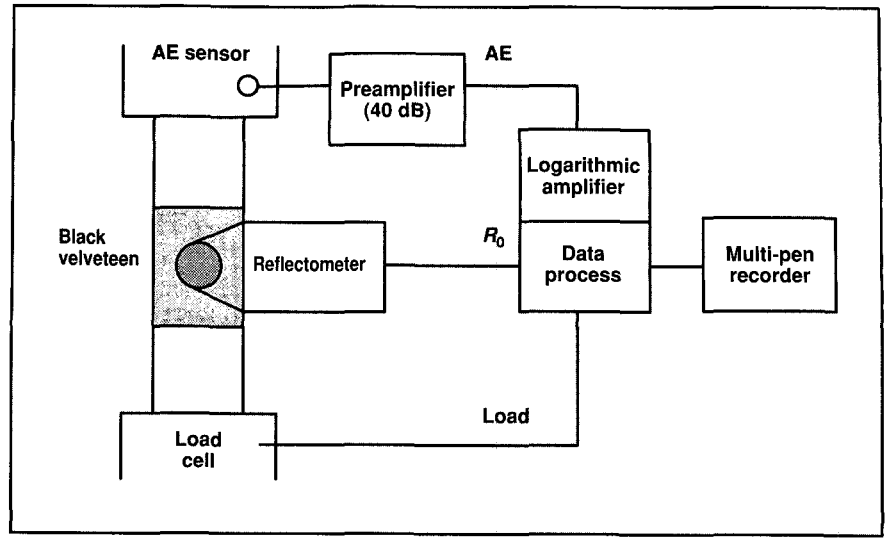
Optical measurement. A photovoltaic-type reflectometer with an FMY/C filter was placed perpendicular to the surface of the specimen. The circular aperture of the reflectometer (10-mm diam.) was in nearly close contact with the specimen and was adjusted to the center of the specimen. Reflectance (R_0) was measured with a black velvet backing during the straining. The usual R_0 and R_∞ measurements

before straining and after straining to failure were also made at several points on the specimen.

Reflectance measurement provides a sufficiently accurate estimate of the change in the scattering coefficient of the paper specimen (*5*). The scattering coefficient was calculated from the values of the measured R_0, R_∞ and basis weight using the Kubelka–Munk theory.

As seen in Fig. 1, the sensor signals for tensile load, reflectance (R_0), and AE were processed in the AE data processor. Results were recorded with a multi-pen recorder. All measurements were made at 20°C and 65% RH following conditioning of the samples.

1. System for measuring load, reflectance, and AE events



Results and discussion

AE and optical reflectance during straining

Nordman's study (*6*) showed that the increment of the reflectance of a sample undergoing strain was varied throughout the specimen, with the failure zone displaying a pronounced increase in the reflectance.

In the preliminary stage of our study, we used a center-narrowed specimen (center reduced to 15-mm width by semicircular cutting) to ensure that the zone of failure coincided with the aperture of the reflectometer. There was only a slight difference in the increment of the reflectance as measured on the center-narrowed specimen compared with that measured on a typical rectangular specimen. However, the mechanical and AE behavior of the center-narrowed specimen differed considerably from that of conventionally shaped specimens. Rectangular specimens were used throughout our previous studies (*1–3*), and we chose to use them again in this study for the sake of continuity.

Figure 2 shows the simultaneous mechanical, optical, and AE responses of the handsheets during strain to failure. The AE results were almost the same as those in a previous report (*1*). The elongation at which AE began to occur increased with degree of beating. For the unbeaten pulp sheet, AE was detected immediately after the elastic deformation. For the beaten pulp sheets, AE was not detected until almost halfway through the plastic deformation in the load–elongation relationship. AE occurred most frequently at or after maximum loading, namely at the moment of fracturing.

On the other hand, the optical reflectance of the handsheet from moderately beaten pulp started to increase at elongation of about 1%—before the first occurrence of an AE event—and continued to increase linearly to failure. The results for the handsheet from lightly beaten pulp are similar to those for the handsheet from moderately beaten pulp. In contrast, the reflectance of the handsheet from unbeaten pulp showed only a faint increase with elongation.

The linear increase in optical reflectance with elongation is in agreement with the result obtained by Nordman (*6*). The increase in reflectance also is similar to the increase in scattering coefficient observed after straining at different elongation levels (*4, 7*).

The increase in sheet scattering coefficient—the difference between the initial value before strain and the final value after sheet failure—is shown in **Table I** for the unbeaten, lightly beaten, and moderately beaten pulp handsheets. Table I also shows freeness, sheet density, tensile index, and percent elongation at failure. The increment of scattering coefficient is comparable with that reported previously (*4, 7*). There seems to be a linear relationship between the increase in scattering coefficient and the percent elongation at failure.

Origin of the changes in opacity during tensile straining

The increase in sheet reflectance has been interpreted as an indicator of bond breakage under tensile elongation (*5*). However, Van den Akker and Andersson pointed out two other possible explanations (*10*).

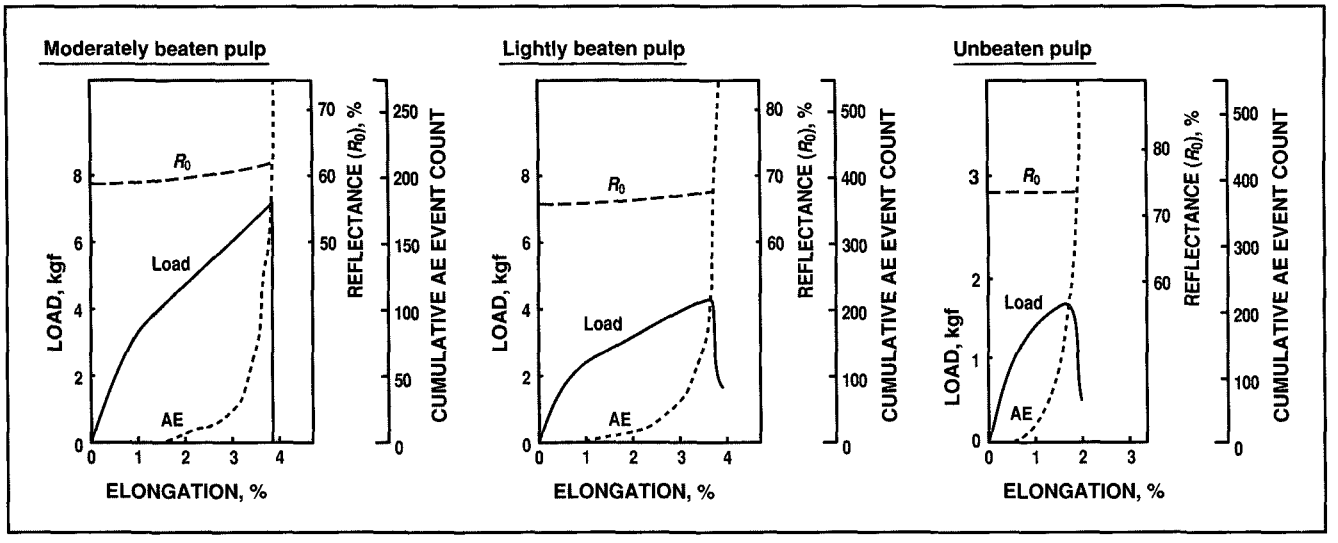
1. Some of the change in reflectance could be caused by the separation of fibers that were not mechanically bound, i.e., in optical contact.
2. The change in reflectance could be caused in part by increased light-scattering power within the fibers.

This second explanation has since been eliminated by experimental results showing that strain has little effect on the amount of light scattered by a fiber (*11*).

The results of our study showed significant differences between the phenomena of AE and optical reflectance during straining.

1. Reflectance increased proportionally with elongation, in contrast to the exponential increase in AE event.

2. Load, reflectance, and AE events as functions of elongation for handsheets from moderately beaten, lightly beaten, and unbeaten pulps (1 kgf load = 9.81 N)

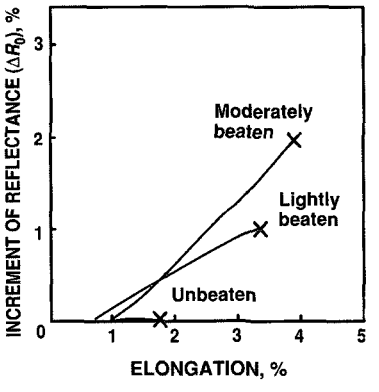


1. Handsheet properties

	Degree of beating, revs. in PFI mill		
	0	2000	5000
Freeness, mL CSF	690	660	465
Sheet density,[a] kg/m³	520	650	795
Tensile index, N·m/g	16	60	71
Increase in scatt. coeff.,[b] cm²/g	4	34	34
Elongation at failure, %	1.9	3.4	3.8

[a]Density determined using thickness as measured by the rubber-platen method (*8, 9*)
[b]Difference in sheet scattering coefficient before strain and after failure

3. Increment of reflectance as a function of elongation (x = failure point)



2. The handsheet from unbeaten pulp gave a large AE event count at failure but a small increase in reflectance, compared with those of the handsheets from beaten pulp.
3. The percent elongation at which AE events began to occur increased with beating degree, from about 0.5% for the unbeaten pulp to about 1.5% for the moderately beaten pulp. On the other hand, the elongation at which the reflectance began to increase was nearly constant at about 1%, regardless of beating degree.

Considering that AE is mainly caused by the cleavage of fiber–fiber bonds (*3*), the experimental results obtained here could suggest that the increase in reflectance was caused by separation of fibers in optical contact. Concomitantly, the separation of optical contact often follows bond breakage.

Structural changes during tensile straining

Figure 3 shows the optical response of the handsheets during straining to failure in more detail. The slope of the relationship between the increment of reflectance and elongation increased with increasing beating degree. The lower increment of reflectance for less-beaten pulp sheets at breakage is partly the result of the lower value of elongation at failure and partly the lower slope of this relationship.

These results seem to be in agreement with concepts about fiber bonding, in which beating increases the optically contacted area as well as the mechanically bound area (*12, 13*). The increased optical contact by beating would imply greater separation of optical contact during straining, resulting in a higher slope at a higher degree of beating.

The optical and AE responses during straining, therefore, reflect the occurrence of two different types of structural change in a sheet undergoing tensile strain. The optical response indicates that the structural change relating directly to the separation of optical contact increases proportion-

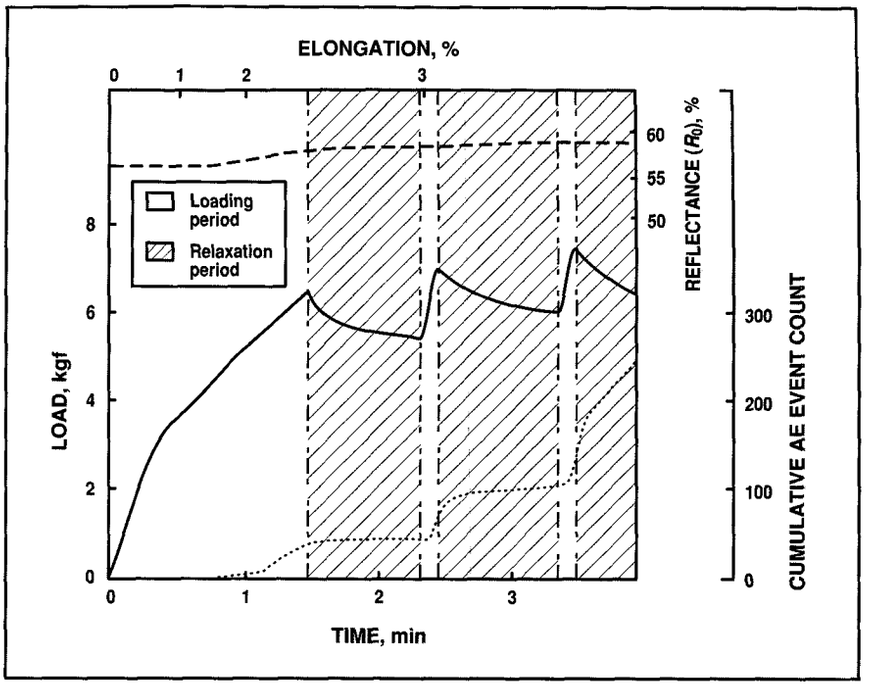
ally with the irreversible elongation. The AE response, on the other hand, shows that the structural change relating directly to bond breakage increases exponentially with increasing elongation. The former structural change is in the wavelength scale, while the size of the latter is in the molecular or submolecular scale.

AE and optical reflectance during cyclic straining and relaxation

Tests involving cyclic straining and relaxation could provide more information on optical and AE behavior with deformation (5). During preliminary cyclic testing, it was found that when the strain on a sheet was relaxed, there was little or no detectable change in optical reflectance and a slight increase in AE event count. When the sheet was subsequently strained beyond the maximum load of the previous cycle, there was a further increase in both optical reflectance and AE event count.

Figure 4 shows the mechanical, optical, and AE results under cyclic strain and relaxation as a function of time for the sheet from moderately beaten pulp. There was no detectable change in reflectance during the relaxation period, and the first restraining beyond the previous maximum load gave a faint increase in the reflectance. On the other hand, the AE event count continued to increase in the beginning of the relaxation period before gradually leveling off. The second period of strain beyond the previous maximum load gave a rapid rise in the AE event count curve. During the following relaxation period—with the load close to the breaking load, the AE event count continued to increase although at a slower rate. These results appear to indicate that bond breakage continues to occur during periods of relaxation, while separation of optical contact between fibers does not.

4. Effect of cyclic loading and relaxation on load, reflectance, and AE event count for handsheet produced from moderately beaten pulp



Conclusion

Paper sheets under tensile load show an increase in optical reflectance. The results presented here suggest that this phenomenon could be directly caused by an increase in the optically unbonded area, i.e., the separation of fibers in optical contact.

Beating the pulp increases the area in optical contact as well as the area of mechanical fiber–fiber bonds. Fibers in optical or mechanical contact can be separated during tensile straining. The results presented in this report suggest that a paper sheet under tensile strain experiences at least two types of structural change. One type of change—optical reflectance—occurs on the wavelength scale and increases proportionally with irreversible tensile elongation. The other type of change—breakage of fiber–fiber bonds—occurs on the molecular or submolecular scale and increases exponentially with tensile elongation. TJ

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