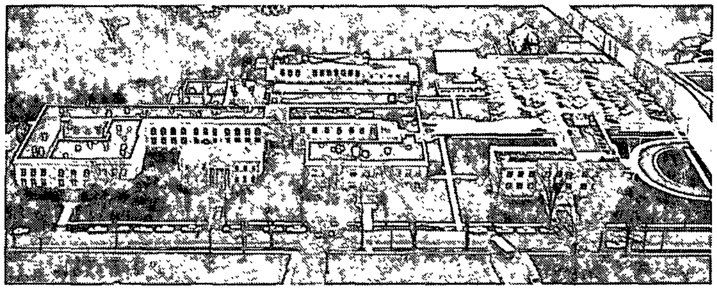

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AN OPTICAL TRANSMISSION METER FOR BOARD-WEIGHT PAPERS

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An Optical Transmission Meter for Board-Weight Papers

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For Members Only

An optical transmission meter for board-weight papers

Keith W. Hardacker[1]

ABSTRACT

An instrument is described which can measure R_0 reflectance by means of a specific calibration and, based on the method of Knox and Wahren, internal transmittance over a range of about 5×10^{-8} to 1. This permits use of the Kubelka-Munk equations to determine the specific scattering coefficients of dark and heavy papers. It is pointed out that the method assumes specimens to be homogeneous in the thickness direction. Examples are given.

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[1] Retired. Work performed at The Institute of Paper Chemistry, Appleton, WI 54912.

Introduction

The degree of bonding of paper is commonly estimated from the specific light-scattering coefficient (s) as determined, with the aid of the Kubelka-Munk equations, from the reflectance of a single sheet over a black body (R_o) and the reflectance of a stack of sheets thick enough that addition of another sheet does not change the reflectance value (R_∞).[1] For dark or board-weight papers, there is little difference between R_o and R_∞; consequently, the calculation is imprecise.

The Kubelka-Munk equations also permit calculation of the specific scattering coefficient from measured values of R_o and transmittance (T); but the T required is the internal transmittance, not the directly measured transmission. Knox and Wahren[2] have shown how Kubelka's[3] equations may be used to calculate this internal transmittance. In essence, a three-layer sandwich is formed with a diffusing top sheet of Teflon, the specimen, and a diffusing bottom sheet of Teflon. Then

$$T_S = f(R_T, R_S, R_B, T_{TSB}, T_{TB}),$$

where T_S = internal transmittance of the specimen

R_T = R_o reflectance of the top Teflon sheet

R_S = R_o reflectance of the specimen

R_B = R_o reflectance of the bottom Teflon sheet

T_{TSB} = instrumentally measured diffuse transmission of the three-layer sandwich

T_{TB} = instrumentally measured diffuse transmission of the top and bottom Teflon sheets only.

The R_0 values are those measured on a diffuse illumination, normal reading reflectance instrument, such as the TB-1 brightness tester.

Knox and Wahren describe an instrument suitable for making the transmission measurements and demonstrate that good agreement is gotten between specific scattering coefficient values of lightweight papers using R_0 and R_∞ values and those using R_0 and T values. They also successfully measured the transmittances of several unbleached corrugating mediums.

New Instrument

A new instrument has subsequently been constructed, incorporating several improvements to increase the measurement range and greatly facilitate the ease of use. Chief among these are the use of flash illumination and ac coupling of the transmitted light signal. The first permits using a very high light intensity for measuring dark, heavy specimens without overheating them, while the second eliminates the need for elaborate shielding against leakage of small amounts of room light. The capability of measuring reflectance was also incorporated so that an additional instrument would not be needed for this.

Figure 1 is a schematic of the new instrument, the Board Optical Transmission Meter (BOTM). It consists of two cast aluminum cubes, nine inches on a side, with an eight-inch diameter, barium sulfate lined, spherical cavity in each. The upper cube is rigidly mounted, while an air actuator can raise the linear-bearing-mounted lower cube to clamp the specimen sandwich between the specimen ports of the spheres. The upper port is 0.80 inch in diameter; the lower, 1.19 inches. A single 4.5-inch diameter, sponge rubber, "O-ring" set into the bottom face of the upper cubes has proved adequate for light shielding.

(Fig. 1 here)

Source

A 150 Joules/flash, xenon flash lamp is mounted in a housing on the side of the upper cube. Before entering the sphere, the radiation is passed through an infrared absorbing filter to reduce heating effects and through an ultraviolet-absorbing filter to minimize specimen fluorescence. Since the flashlamp output varies from flash to flash, the intensity of the illumination in the sphere is sensed by a silicon photodetector in another housing bolted to the side of the cube. Optical filters in the source (S) detector port and in similar filters in the reflectance (R) and transmission (T) detector ports result in a system response approximating the CIE Y-function for Illuminant A.

Reflectance and Transmission Detectors

A second silicon photodetector is contained in a housing on top of the upper cube and is provided with optics so that it sees only the specimen. Thus, it responds to specimen reflectance.

Detection of the transmitted light requires a photomultiplier tube (PMT) to provide the required combination of high sensitivity and high speed response. This detector is mounted in a housing bolted to the lower cube. Because of the very wide range of light levels to be measured, a wheel allowing selection of four different sized apertures is placed between the PMT and its sphere port. These apertures, used in conjunction with two different PMT supply voltages, permit measuring transmittances from 1 down to about 5×10^{-8}.

Specimen Sandwich

The top and bottom sheets of the specimen sandwich are 1/8 x 9 x 9-inch sheets of PTFE Teflon. A circle two inches in diameter is scribed at the center of the lower sheet to facilitate placement of the specimen as the sandwich is assembled before being placed between the cubes.

Signal Handling

Each of the three light detectors is followed by an analog peak-detection circuit, which holds the signal corresponding to the peak light level sensed during each measurement cycle. Since the PMT senses both the pulse of light transmitted through the specimen and any small leakage of ambient light, its preamplifier is ac coupled to its peak detector in order that the latter will respond only to the light pulse. Digital panel meters convert the peak levels to arbitrarily scaled digital readings (T_m, R_m, and S_m) for manual recording.

Results

Reflectance measurements

Measurements of R_o can be made using a specific calibration of the BOTM readings *vs.* the TB-1 readings of the same specimens. The lower sphere approximates a black body, so reflectance readings of a bare specimen (no top or bottom Teflon sheets) clamped between the cubes may be used. To facilitate specimen handling, however, a 1/2 x 9 x 9-inch polyethylene sheet with a 1.75-inch diameter, black felt lined cavity in its center was made and used as the specimen carrier and black body.

Table I describes the wide range of samples used throughout the development testing (and additional data to be discussed later). A specific calibration plot of the BOTM R_m/S_m readings of these samples made with no cover (bare) and backed with the black body is shown in Fig. 2. Deviations from the linear regression line are generally small, and since they occur primarily with the colored samples, are suspected to be caused by some mismatch between the spectral characteristics of the BOTM and the TB-1.

(Table I and Fig. 2 here)

BOTM reflectance readings were also made with the specimens in the Teflon sandwich. The nonlinear relationship to the R_o [TB-1] values is shown in Fig. 3. More scatter of the data is apparent and may be due to both the decreased sensitivity of the measurement and, in the case of the colored samples, a possible additional spectral contribution from the Teflon diffusing sheets.

(Fig. 3 here)

Using the BOTM to measure both transmittance and reflectance of a sandwiched specimen simultaneously is desirable because specimen handling is reduced: the additional step of inserting and reading the black-body-backed specimen is not needed. Also, this procedure results in the reflectance and transmittance readings being taken on exactly the same area of the specimen. A disadvantage lies in the fact that the sensitivity to R_o (i.e., the range of R_m/S_m values) for the "sandwiched" readings of Fig. 3 is only about 15% that of the bare specimen, black-body-backed readings of Fig. 2. Thus, for best accuracy, R_o should be determined either from a specific calibration of the bare specimen, black-body-backed BOTM readings <u>of the specimen types to be read</u> or from the TB-1.

In accord with the well known behavior of other reflectance measuring instruments, tests showed that small changes of separation of the specimen from the specimen port of the BOTM cause some change in the reflectance reading. Thus, for measurement of R_o, the specimens must be maintained in flat contact with the port opening during both the specific calibration and the measurement.

Transmittance Measurements

A check was made of the agreement between internal transmittance values of lightweight papers measured on the BOTM (using TB-1 values of R_0) and values calculated from R_0 and R_∞ readings on the TB-1. The results, shown in Table II, demonstrate good agreement. Where the colored samples show somewhat poorer agreement, it is suspected that the spectral responses of the two instruments need to be more closely matched.

(Table II here)

To calibrate the PMT port (aperture) sizes and the gains with the two PMT voltages used - and also to demonstrate the range of transmittances measurable - BOTM readings were made of stacks of sample A. Figure 4 is a plot of the results, which shows that transmittances can be measured down to about 5×10^{-8}.

(Fig. 4 here)

As a check for any effect on the transmittance readings due to a small-sized specimen, readings were taken of a 206 g/m^2 unbleached linerboard as its size was reduced from 9 x 9 inches to a 1.5-inch diameter disk. No change of calculated transmittance reading was obtained.

An additional test was made with the same linerboard by placing spacers (file folder stock with two-inch diameter holes) between the specimen and each Teflon sheet to create air gaps. In contrast to the reflectance measurements, no change of readings was observed as the gaps changed from 0 to 0.011 to 0.022 inch. Use of spacers thus makes it possible to test soft specimens without crushing them. The air gap insensitivity also suggests that transmittance might be measured on-line without making physical contact with the web.

The Knox and Wahren implementation of the Kubelka equations for calculating T_S assumes that each layer of the three-layer sandwich is homogeneous in the sheet thickness direction. When the paper sample is composed of two or more layers which differ from each other, such as exists with many linerboards, the sample is nonhomogeneous and may itself be considered to consist of two or more homogeneous layers. The Kubelka equations show that the calculated transmittance of a nonsymetrical, nonhomogeneous specimen in the Teflon sandwich will depend upon which side of the specimen is up.

Table I shows the results of measurements made with each side of each specimen uppermost in the Teflon sandwich and demonstrates that there is a significant difference in the calculated values of T_S for those specimens suspected of being multi-ply (H, I, J, and M). These latter T_S values result from some undetermined combination of the transmittance and reflectance values of the separate plies of the specimen, so do not permit determination of the individual ply values. This should be borne in mind when using the results of BOTM measurements made on nonhomogeneous sheets.

Scattering Coefficient

Remembering that the purpose of the BOTM is to enable making measurements for the estimation of the bonded area within a sheet, two columns of Table I list the scattering power ($\underline{sW}$) and the specific scattering coefficient ($\underline{s}$) calculated for the samples. While these are quantitative values for the homogeneous specimens, they should be considered more as qualitative guides - but very useful guides - for the nonhomogeneous specimens.

A specific absorption coefficient ($\underline{k}$) may also be calculated from the data:

$$\underline{k} = \underline{s}\ (a-1)$$

where

$$a = (1 + R_o^2 - T^2)/2R_o.$$

For completeness, the $\underline{k}$ values have been calculated for the samples and are listed in the last column of Table I. Since these, like the $\underline{s}$ values, utilize the BOTM-derived values of T, they should be considered only as qualitative guides for the multi-ply specimens.

Scattering coefficient measurements were also made on several board-weight sheets prepared as part of the doctoral thesis of Berger.[4] These were handsheets of about 275 g/m^2 grammage made from loblolly pine fibers, kraft pulped to a kappa number of 25. Portions of the pulp were refined to various levels in a PFI mill, and the sheets were wet pressed at several levels to obtain a wide range of sheet densities. Figure 5 shows that, as expected, both increased refining and increased wet pressing pressure give sheets of higher density and lower specific scattering. The latter is interpreted as an increase in the fiber-fiber bonding within the sheet.

(Fig. 5 here)

Summary

An easy to use instrument for measuring the internal transmittance of dark and heavy papers, using the technique of Knox and Wahren, is described. Transmittances of white papers as low as 5 x 10^{-8} are readily determined. An R_o reflectance can also be measured simultaneously (i.e., with the specimen in the three-sheet Teflon sandwich required for the transmittance measurement), but the

sensitivity is low. Best results are gotten using R_o values from another instrument, such as the TB-1 brightness tester.

The Knox and Wahren technique for measuring transmittance assumes that the specimen is homogeneous in the thickness direction. When this condition is not met - as, e.g., for most multi-ply boards - the measured transmittance is some undetermined combination of the local reflectance and transmittance values through the sheet. Also, for a nonsymmetrical specimen, the measured transmittance depends upon which side of the sheet is toward the source. These transmittances, although not the true transmittances which are calculated for homogeneous sheets, can be helpful guides nonetheless.

The usefulness of the instrument is demonstrated with measurements of the transmittance, specific scattering coefficient, and specific absorption coefficient of a wide range of papers, from a 39 g/m^2 white bond to a 434 g/m^2 unbleached kraft linerboard. The two-sided effect of multi-ply papers is also demonstrated.

Literature Cited

1. Arnold, E. W. Light scattering in fibrous sheets. Tappi 46(4):250-6 (April, 1963).

2. Knox, J. M.; Wahren, D. Determination of light scattering coefficient of dark and heavy sheets. Tappi J. 67(8):82-5(Aug., 1984).

3. Kubelka, P. New contributions to the optics of intensely light-scattering materials. Part II. Nonhomogeneous layers. J. Opt. Soc. Am. 44(4):330-5 (April, 1954).

4. Berger, B. F. The effects of yield and refining on the z-direction elastic properties of paper. Doctoral Dissertation, Appleton, WI, The Institute of Paper Chemistry, 1988.

I. Characteristics of the samples.

Sample	BW, g/m²	BOTM					TB-1	T	sW	s, cm²/g	k, cm²/g
		T-Port	PMT-V	T Meter	R Meter	S Meter	R_o				
A. White bond											
Felt side	39.2	A	700	315	912	766	0.730	1.87e-1	3.51	895	23.3
Wire side				319	919	771	0.727	1.90e-1	3.45	880	23.4
B. White bond	77.1	A	700	328	932	784	0.718	1.96e-1	3.30	428	12.2
				320	900	760	0.720	1.96e-1	3.32	430	11.9
C. Pink memo	76.4	A	700	222	901	774	0.592	1.96e-1	2.43	318	35.3
				221	898	772	0.584	2.00e-1	2.36	309	34.5
D. Deinked	69.7	A	700	217	895	764	0.710	1.43e-1	3.95	567	25.5
				246	926	785	0.705	1.59e-1	3.66	526	23.1
E. Yellow memo*	75.1	A	700	413	924	771	0.710	2.45e-1	2.78	370	6.33
				414	932	777	0.709	2.44e-1	2.77	369	6.52
F. Cream tab	162	A	700	274	941	784	0.757	1.50e-1	4.34	268	5.76
card stock				288	944	785	0.762	1.54e-1	4.32	267	6.48
G. Blue cover*	250	C	1000	515	853	769	0.475	3.87e-5	12.15	486	141
				502	862	778	0.466	3.81e-5	11.82	473	145
H. Unbl. medium	131	C	700	272	824	764	0.182	6.39e-4	2.76	210	387
				269	836	770	0.242	5.66e-4	3.81	291	346
I. Semi-bl.	159	B	1000	370	859	778	0.370	7.41e-3	4.08	257	138
medium				369	858	775	0.389	7.14e-3	4.38	276	132
J. Unbl. liner	339	D	1000	420	845	774	0.277	1.42e-5	6.65	196	185
				391	848	775	0.291	1.29e-5	7.10	210	181
L. Buff cover	163	A	1000	247	895	781	0.621	1.21e-2	7.94	487	56.4
				251	904	785	0.628	1.20e-2	8.14	499	55.0
M. Unbl. liner	434	D	1000	37	851	779	0.272	1.26e-6	7.94	183	178
				33	846	772	0.298	1.08e-6	8.93	206	170
N. White bond	72.4	A	700	315	945	781	0.796	1.51e-1	4.82	666	7.91
(fluores.)*				313	939	777	0.799	1.49e-1	4.90	676	7.69
P. Whatman #1,	72.2	A	700	477	949	785	0.732	2.54e-1	2.84	394	2.02
creped*				474	942	779	0.731	2.55e-1	2.83	392	2.03
Q. Whatman #1,	88.4	A	700	446	961	790	0.774	2.13e-1	3.57	404	1.46
smooth*				440	941	775	0.772	2.16e-1	3.53	399	1.44

One reading per sample per side.

*Felt and wire sides indeterminable.

II. Internal transmittance values of lightweight sheets.

	Sample	TB-1 (Y-Function)			BOTM	
		R_o	R_∞	T_S	T_A	T_S
A.	White bond	0.728	0.799	0.192	0.453	0.193
B.	White bond	0.721	0.780	0.205	0.490	0.210
C.	Pink memo	0.584	0.633	0.221	0.308	0.204
D.	Deinked	0.708	0.750	0.162	0.366	0.171
E.	Yellow memo	0.721	0.823	0.225	0.500	0.214
F.	Cream tab card stock	0.767	0.815	0.148	0.378	0.147

Readings are the average of one reading on each of five specimens.

T_S [TB-1] = $\mathrm{SQRT}(R_o{}^2+1-(R_o*(1/R_\infty+R_\infty)))$.

T_A [BOTM] = T_{TSB}/T_{TB}

T_S [BOTM] = $(1-1/R_T*R_B))/(2*T_A)+(((1-1/R_T*R_B))/(2*T_A))^2$
$+((1/R_T)-R_S)*((1/R_B)-R_S))^{0.5}$

Figure Captions

Figure 1. Schematic of the Board Optical Transmission Meter.

Figure 2. The relationship of the R_m/S_m BOTM readings of Table I specimens backed with a black body to the R_0 readings from the TB-1 brightness tester.

Figure 3. The relationship of the R_m/S_m BOTM readings of Table I specimens in the Teflon sandwich to the R_0 readings from the TB-1 brightness tester.

Figure 4. Logarithm of the calculated internal transmittance of stacks of Sample A (39.2 g/m^2) vs. the number of sheets in the stack. Values for 162 readings are plotted, using overlapping ranges of the 4 T-ports and both PMT voltages.

Figure 5. The specific scattering coefficient vs. the density of approximately 275 g/m^2 handsheets of loblolly pine kraft pulp refined to various levels in a PFI mill and wet pressed at several pressures. The first number accompanying each plotted point is the number of revolutions of the PFI mill; the second, the wet pressing pressure in psi.

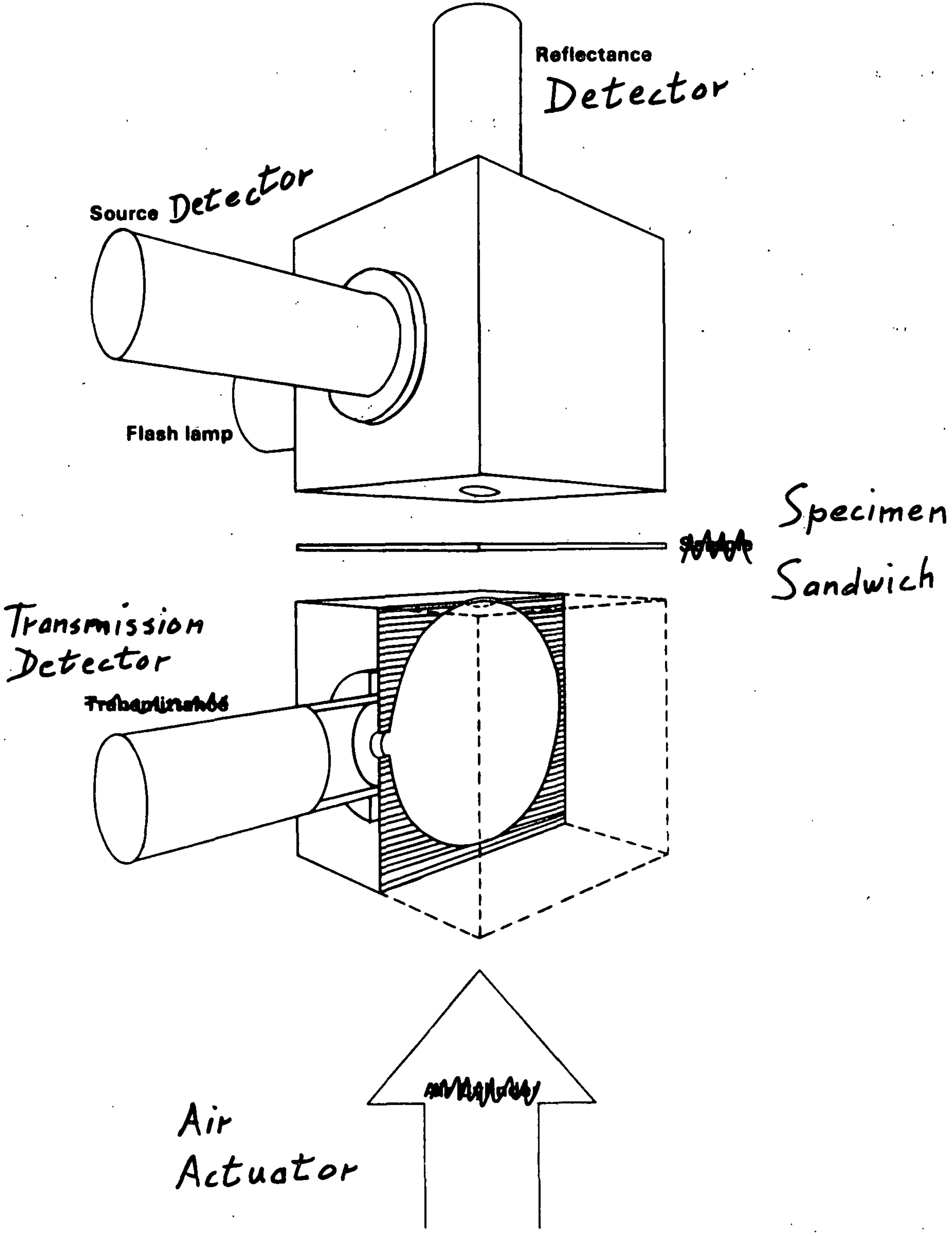
Reflectance
Detector
Source
Detector
Flash lamp
Specimen
Sandwich
Transmission
Detector
Air
Actuator

FIG. 1

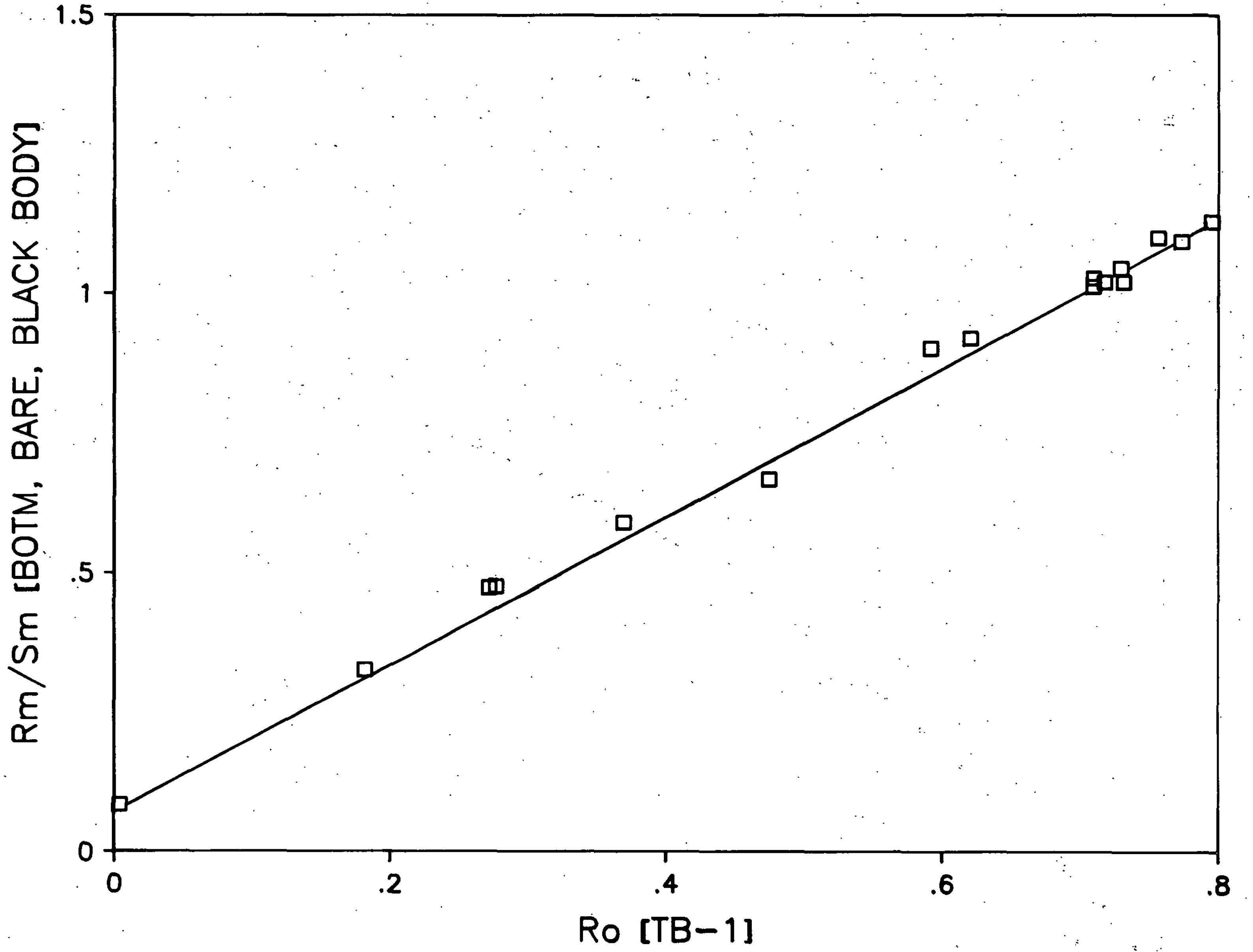

FIG. 2

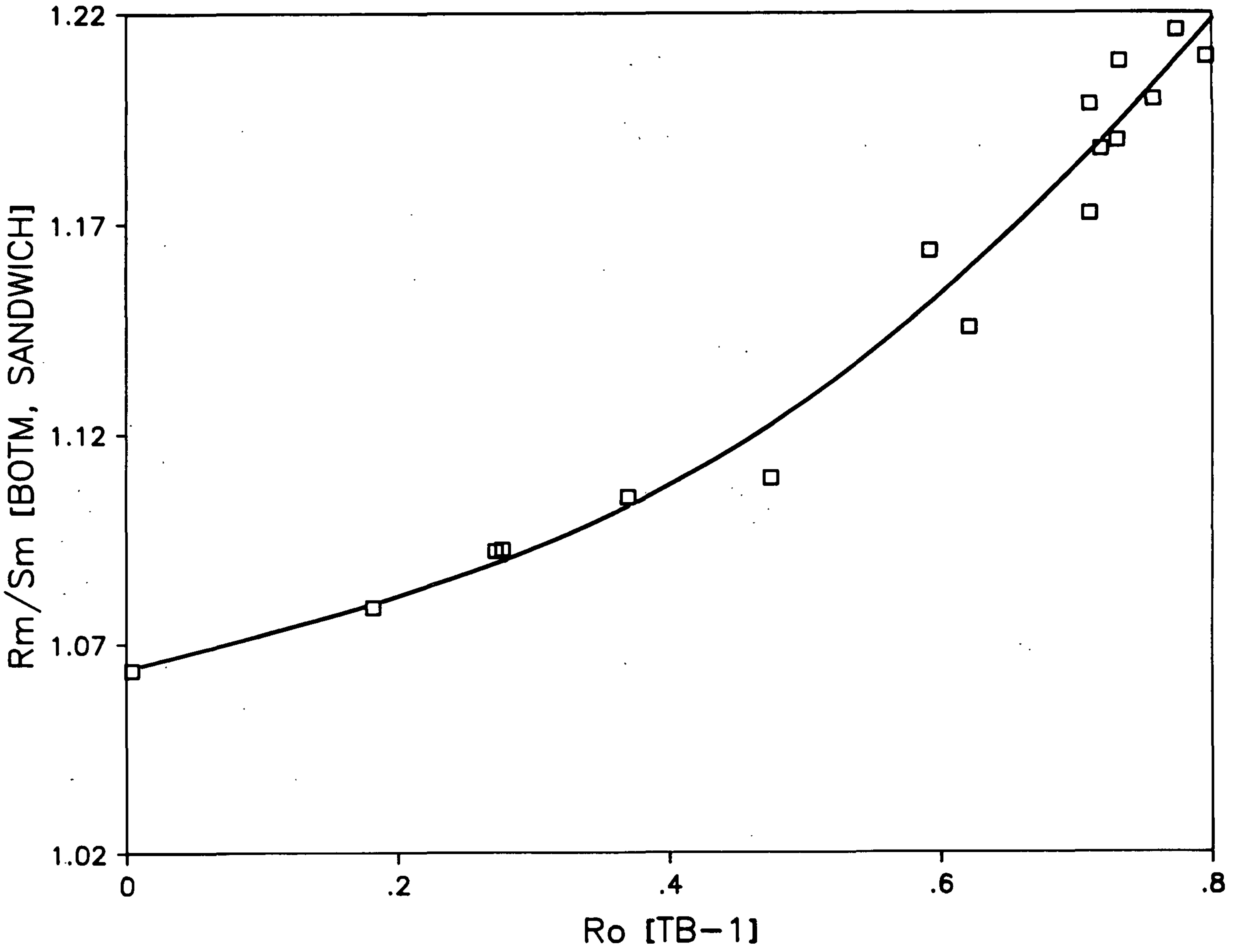

Fig. 3

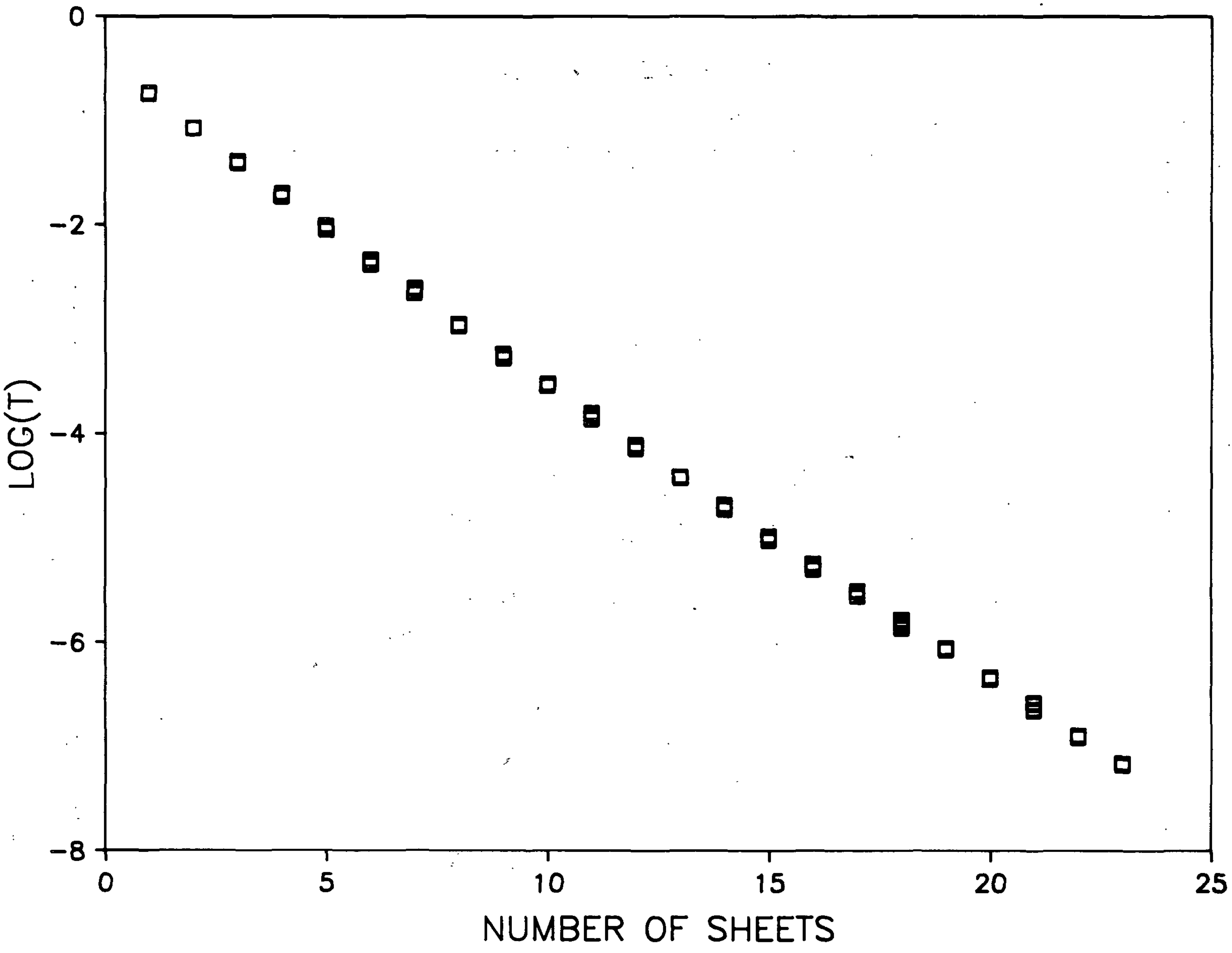

FIG. 4

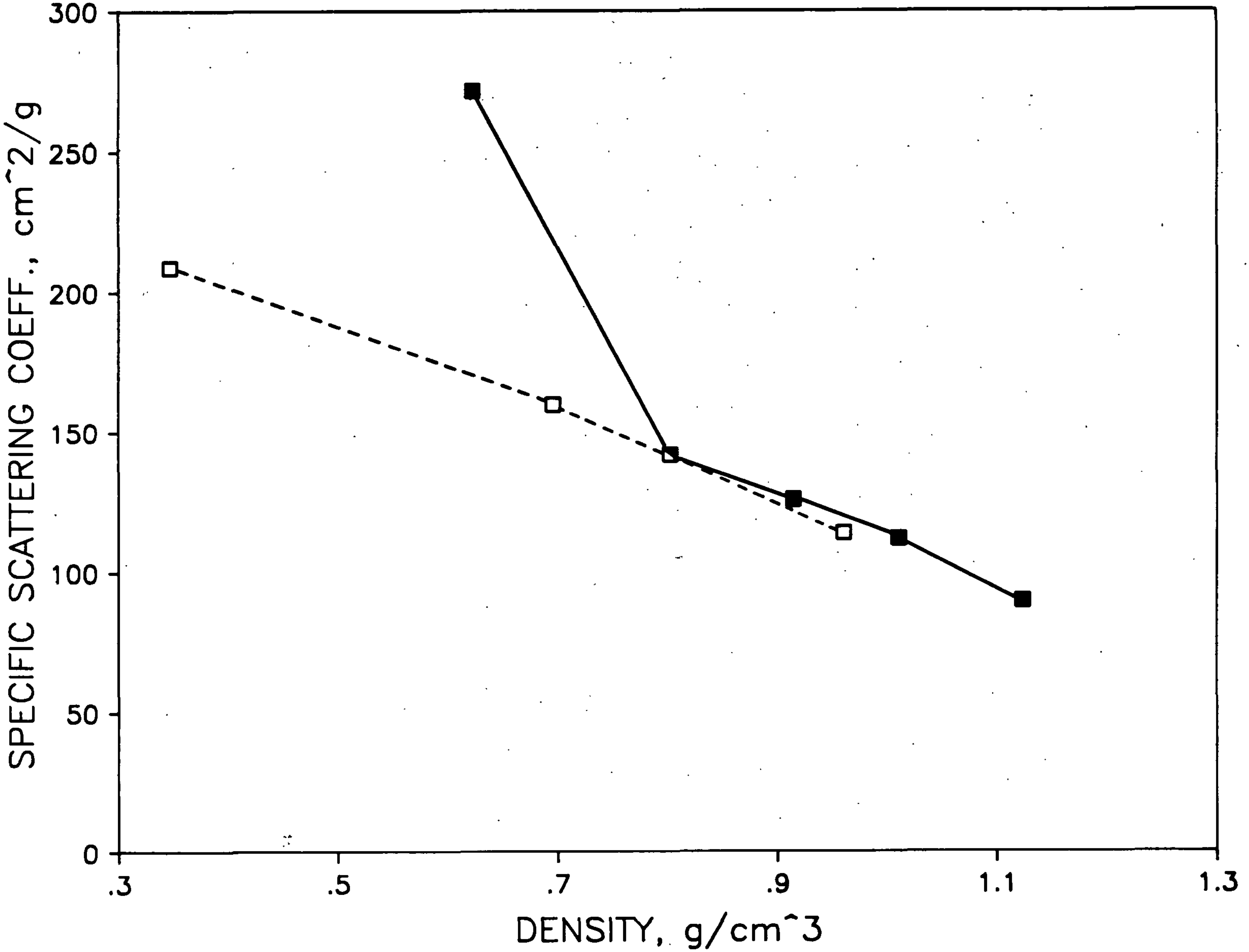
300
250
200
150
100
50
0
SPECIFIC SCATTERING COEFF., cm^2/g
.3
.5
.7
.9
1.1
1.3
DENSITY, g/cm^3

FIG. 5