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Optical Characteristics of Paper as a Function
of Fiber Classification

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**OPTICAL CHARACTERISTICS OF PAPER
AS A FUNCTION OF FIBER CLASSIFICATION**

A thesis submitted by

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INTRODUCTION

The development in comparatively recent times of photoelectric instruments for the objective measurement of the light reflectance of paper has made the accurate measurement of the common optical properties of paper, such as opacity and spectral reflectance, a routine matter. In the past decade, as a result of this, greater development has been made in the study of the optical properties than in any of the other physical properties of paper.

The effects of beating, loading, dyeing, coating, and calendaring on the optical properties of a paper sheet have been the subject of considerable investigation in the past few years. However, very little fundamental work has been done on the effect of fiber dimensions on these properties.

It is the purpose of this investigation to make a fundamental study of the effect of fiber dimensions on the optical characteristics of a paper sheet.

II

DEFINITION OF TERMS

$O_{.89}$ = TAPPI opacity -- $R_0/R_{.89}$

K = Absorption coefficient, the limiting value of the relative absorption of light energy per unit thickness as the thickness of an imaginary layer of the material becomes very small.

R = Reflectance, or the fraction of incident light reflected from a sample.

R_R = Reflectance of material backed by a body of reflectance R' .

R_∞ = Reflectivity, or reflectance of material backed by an opaque pad of the same material.

R_0 = Reflectance of material when backed by a body having a reflectance of zero.

$R_{.97}$ = Reflectance of material when backed by a body having a reflectance of 0.97.

$R_{.89}$ = Reflectance of material when backed by a body having a reflectance of 0.89.

S = Scattering coefficient, the limiting value of the relative light energy per unit thickness scattered backwards from an imaginary layer of a material as the thickness of the layer becomes very small.

X = Caliper

W = Basic weight

mm = Millimicron

HISTORICAL SURVEY

The common optical properties of a paper sheet include opacity, transparency, reflectance, and gloss. Of these, the two most important are opacity and reflectivity (transparency is the antithesis of opacity; so any factors influencing opacity also influence transparency). One reason for the importance of these two measurements is that they are useful criteria of pulp quality -- opacity and brightness of a paper sheet are influenced greatly by the type of fiber used. High transparency and gloss are the results of special treatments of the pulp and of the paper sheet. The term reflectivity refers to the diffuse reflectance of an opaque pad of material. This measurement is often made on an abridged spectrophotometer at an effective light wavelength of about 495 nm and the reflectivity measurement thus obtained is referred to as "brightness" in the paper industry. Of more general usefulness is "spectral reflectance" -- a curve giving reflectance as a function of wavelength; from this curve colorimetric data may be obtained. The accepted measurement of opacity is contrast ratio, which is the ratio of two reflectance values -- viz, the ratio of the reflectance of the sheet when backed by a black body to the reflectance of the sheet backed by a "white" body. There are two commonly accepted contrast ratios: (1) TAPPI opacity, in which the white body has an absolute reflectance of 0.89, and (2) printing opacity, in which the white body is an opaque pad of the paper itself.

It is thus seen that, in studies of the optical characteristics of a paper sheet, reflectance measurements are of the greatest value. It should be noted, however, that in certain instruments opacity is determined by means of a transmittance measurement. Use requirements of paper, however, dictate that the most significant measurement of opacity is that given by reflectance values such as in the contrast ratio measurement.

Harrison (1) has summarized the various relationships that have been developed in the mathematical treatment of the light reflectance and transmittance of translucent materials. The most important of these equations are those of Hyde (2), Garavito (3), and Kubelka and Munk (4). These equations relate the reflectance of thin layers of a homogeneous material in terms of fundamental constants.

The equations of Kubelka and Munk are the most readily applicable to practical measurement, because these investigators carried out their derivation in such a way that the quantities measured are simple reflectance measurements. The application of the Kubelka and Munk equation to paper has been studied by Steele (5) and Judd (6). By means of these equations the diffuse reflectance values of a paper sheet may be related in terms of two fundamental constants, the scattering coefficient, \underline{S} , and the absorption coefficient, \underline{K} .

A useful equation of the Kubelka and Munk theory is:

$$\underline{K}/\underline{S} = (1 - \underline{R}_{\infty})^2 / 2\underline{R}_{\infty}$$

From this relation the ratio of \underline{K} to \underline{S} may be evaluated by a simple reflectivity measurement. Other equations permit the calculation of

charts by means of which \underline{S} and subsequently \underline{K} may be evaluated. Steele (5) has published charts of this type. A chart developed by the National Bureau of Standards, which has found quite widespread use, shows the interrelation of \underline{R}_0 , \underline{R}_{∞} and $\underline{Q}_{.89}$.

The scattering and absorption coefficients are characteristic of the pulp fibers making up a sheet. Simple changes in a sheet, such as variations of the basis weight, would have very little effect on these coefficients. It is this fact that makes these coefficients, particularly the scattering coefficient, of value in predicting changes of opacity with changes of basis weight.

Roote (7) and Probst (8) give data showing the variation of the scattering and absorption coefficients over the visible light spectrum. These data show that the scattering coefficient decreases with increasing wavelength of light. This decrease may be due to one of two things. As shown by Frey-Nysling (9), the index of refraction of cellulose fibers shows a slight decrease with increasing wavelength of light. The decrease in the axial index of refraction of ramie fiber is from 1.6083 at 486 mm to 1.5969 at 656 mm. Roote (7) found that the $\underline{S\bar{K}}$ value of a paper sheet formed from bleached sulfite pulp decreased from 1.12 at 500 mm to 1.05 at 670 mm. It would seem doubtful that the small change in the index of refraction is sufficient to explain the larger change in the scattering coefficient.

Another explanation for the decrease of \underline{S} with the longer wavelengths of light is that some of the scattering of light may take place within the fiber. If this is so, then the Rayleigh law of

scattering would hold here, in part at least, since the particle size of structural units within the fiber are of the same magnitude as the wavelength of light. The Rayleigh law states that the intensity of light scattered from particles smaller than the wavelength of light varies inversely with the fourth power of the wavelength.

The optical impression of opacity of cellulose fibers is derived in part from the scattering of light from the many discontinuous surfaces in a paper sheet. The high absorption coefficient of unbleached pulps cause such pulps to have high opacity. Paper makers for many years have recognized that certain types of pulps impart opacity to a paper sheet. The pulp that has been used most commonly for this purpose is bleached hardwood soda, Groundwood, straw, and esparto are other types of high opacity pulps. The use of repulped dry broke to improve opacity is apparently practiced in some mills (10).

Little is to be found in the literature concerning the opacity of different pulps. Reischler (11) gives data showing the higher opacity of kraft pulps as compared with sulfite pulps. He states that an increase in opacity is obtained with the short-fibered fraction of a pulp over the long-fibered fraction, apparently basing this conclusion on the observation that straw pulp, a short-fibered pulp, is rather opaque.

Unpublished data collected by the students taking the advanced pulping course at the Institute of Paper Chemistry show the following generalities in the case of pulps bleached to the same brightness:

1. Increasing the degree of cooking of the pulp prior to

bleaching, increases the opacity of the bleached pulp.

2. Hardwood pulps in most cases show a much higher opacity than softwood pulps.

Vicker (12) states that transparency depends on the following factors: (1) mechanical structure of the sheet, (2) surface smoothness, (3) foreign materials, and (4) optical contact of fibers in the sheet.

The reason for the higher opacity and scattering coefficient of short-fibered pulps lies in the fact that there are more cellulose-air interfaces within a sheet made from such pulps. Because of the poor bonding qualities of repulped dry broke, it would have a smaller area of optical contact of the fibers and consequently a high opacity. The higher opacity obtained with increasing degrees of cooking is presumably due to a smaller area of optical contact with the more drastically cooked pulp; this, in turn, is due to a poorer bonding of the fibers or to a greater number of discontinuities within the fiber.

Very few data have been published concerning the influence of various fiber fractions of the same pulp on the scattering and absorption coefficients. Lewis (13) states that he cut a pulp from an average fiber length of 2 mm. to 0.5 mm. without changing the values of K_D or K_{D0} .

Mason (14) has published a limited amount of data on the transmittance and reflectance values of different fractions of a sulfite pulp. His data in part are as follows:

Screen fraction	Transmittance
thru 14 on 25	0.366
" 25 " 45	.335
" 45 " 100	.334
" 100 " 200	.309

From these data it is apparent that the short fractions of a pulp are more opaque than are the long ones.

The degree of physical treatment that a pulp has received has a marked effect on the optical properties of the resulting paper sheet. Increased beating of pulp results in a better bonding of the fibers in the sheet and consequently a larger area of optical contact between the fibers. This results in a decreased opacity with an increased degree of beating. A notable exception to this is the result Probst (5) found on beating of a highly purified pulp -- viz, a pulp that had been treated with a sufficient concentration of caustic soda in the cold to cause mercerization. With this pulp the scattering coefficient showed an increase on beating rather than a decrease. Photomicrographs of this pulp after beating showed a considerable degree of fibrillation. Apparently, however, the fiber-to-fiber bonding was poor with this pulp so that increased fibrillation and fiber splitting had the effect of increasing the number of cellulose-air interfaces in the paper sheet.

Fests (7) and Probst (5) both showed that the absorption coefficient of a pulp increases on beating. This seems unusual since the paper sheet becomes more transparent with increased beating.

Feste (8) measured the absorption and scattering coefficients of mixtures of two pulps. His data showed that the absorption coefficient of a 50-50 mixture of bleached and unbleached sulfite pulps was the arithmetic average of the absorption coefficients of the separate pulps. This relation did not hold true for the scattering coefficient of the mixture.

PRESENTATION OF PROBLEM

The approach to a study of the effect of fiber size on the optical characteristics of a paper sheet could be made in at least two ways. One method would be to take several pulps of widely different fiber dimensions and evaluate the optical properties of handsheets formed from these pulps. Pulps to be used in such a study would logically include rag, softwood bleached sulfite, hardwood bleached soda and groundwood pulps. Such a method, however, is subject to criticism, because in addition to variations in the optical effects produced by differences in fiber dimensions, there would be also the marked effect on the optical properties of differences resulting from the physical and chemical treatment of the several pulps. A method which would reduce the number of variables to that of fiber size alone¹ would be to fractionate a given pulp and make optical measurements on handsheets prepared from the different fractions. It was decided that the most logical approach would be the latter method, using several representative pulps.

To avoid unnecessary complications it seemed wise to work with relatively free pulps that had received a minimum of physical treatment.

¹. This statement is made advisedly because it is recognized that different fractions of a pulp may vary slightly in chemical composition and also that sheets made from different fractions of a pulp may vary slightly in density.

It is recognized that these measurements will be of more theoretical than practical importance in the case of chemical pulps, because the fractionation of chemical pulps to give fractions of specified optical properties would be an economic improbability. However, in the case of groundwood, such studies would be of both theoretical and practical interest for with this pulp the particle size may be varied by changing the conditions of grinding.

MATERIALS AND METHODS

A. PULPS USED

The pulps used included a bleached spruce sulfite, bleached hardwood soda, two jack pine kraft pulps in different stages of bleaching, groundwood, bleached poplar sulfite, and a high alpha-cellulose pulp. The spruce sulfite and the soda pulp were in dry lap form; the kraft pulps, the groundwood, and the poplar sulfite were received in wet form with from 70 to 75 per cent water. The groundwood was received just prior to use and so needed no storage. The kraft pulps and part of the poplar sulfite were stored and used in the wet condition. To preserve these pulps, they were sprayed liberally with a one per cent solution of sodium pentachlorophenate and stored in air-tight containers. Part of the poplar sulfite was air dried and stored in paper bags.

The high alpha-cellulose pulp was prepared in the manner described by Probst (5). The dry lap spruce sulfite pulp was used in the preparation of the alpha pulp. This was disintegrated in water, pressed out to about 25 per cent dryness, and treated at a consistency of 3.6 per cent for one hour at 25° C. with a 15 per cent solution (by weight) of sodium hydroxide. The pulp was drained after this treatment and washed with softened water for 15 minutes. Then the pulp was stirred at 4 per cent consistency with 1 per cent acetic acid (by weight) for five minutes. The pulp was again drained, washed for five

minutes with water, and treated with acetic acid. Finally the pulp was drained, washed for five minutes, pressed to 25 per cent dryness, and stored.

B. FRACTIONATION OF PULPS

In the fractionation of a pulp which is to be used for optical measurements, the effect of impurities in the water used on the brightness of the pulp is of great importance. Softened water was used in these fractionations. The water was softened in a Permutit "De-Acidite" system, which is a two unit system, the first unit being the base-exchange unit and the second unit, an acid-absorbing unit. The water passing through this system also passes through an activated carbon filter, which is a third unit that was added to remove a pinkish color in the water coming from the softener. This series of treatments provides a water which may be considered pure as far as its effect on the brightness of pulp is concerned.

Before the pulps were fractionated they were disintegrated in the British disintegrator, using 90 grams of dry pulp in two liters of water. Dry lap pulps were soaked for at least three hours in water and broken up with 25,000 revolutions. Pulps in wet form were soaked in water for a short while and broken up with 12,500 revolutions in the disintegrator, with the exception of groundwood, which was disintegrated with 7,500 revolutions.

The fractionation of the pulps was carried out in a Ransom-McNott fiber classifier, which is provided with 20, 35, 65, and 150-mesh

screens. The standard procedure adopted was as follows: The equivalent of 10 grams of oven-dry pulp in completely defibered form were added to the first compartment of the classifier with the stirrers running, and with water passing through at a given rate of about three gallons per minute. The time of fractionation was 15 minutes. The contents of each compartment were then drained and the fibers caught on a muslin cloth.

The pulps used contained varying amounts of fine material which would pass the 150-mesh screen. (Hereafter in this thesis, the word "fines" will refer to this fraction) Because it was desired to study these fines, provisions had to be made to collect them. At first all of the water passing through the classifier was collected and filtered through a fine mesh muslin cloth. It was found that the fines thus collected were usually rather dirty, particularly in the case of a softwood pulp in which the percentage of fines was very small. In collecting the fines in this way, about 45 gallons of water per classification come into intimate contact with a very small quantity of fines and any dirt in the water appeared to be picked up. One classification was made using distilled water and the fines were collected as above. The fines were still rather dirty, which may have been the result of traces of grease from the bearings of the stirrers. Finally, a method was adopted which avoided the contact of the fines with extremely large quantities of water, and in this way fines were collected that were relatively clean. In the case of a softwood pulp, which contained a very small percentage of fines (usually less than 5%) a large batch of the pulp, about 500 grams dry weight, was soaked

in water and then broken up by a "Lightnin" stirrer. A suspension of the pulp was then run over an inclined screen of about 90 mesh. All the pulp and water passing through this screen were collected in crecks. The short-fibered fraction thus collected was allowed to settle and the supernatant water siphoned off. The concentrated short-fibered pulp was then run through the classifier; all the water passing through the last screen was collected and the fines allowed to settle. The supernatant water was then siphoned off and the concentrated fines filtered on a muslin cloth. The fines thus obtained were in contact with relatively small quantities of water and so were quite clean. In the case of hardwood pulps and groundwood, which contained a large amount of fine material, a slightly different procedure was used. The water passing through the classifier during the first six or seven minutes was collected, since most of the fines would have passed through the last screen by that time. The fines were then allowed to settle, the excess water siphoned off and the concentrated fines filtered as before.

C. PREPARATION OF HANDSHEETS

It was desired to mix together different fractions of a pulp in definite proportions and to measure the scattering and absorption coefficients of handsheets formed from such mixtures. This of course necessitated that there be no loss of fiber in the sheet-forming operation. The standard method of forming handsheets on the British sheet mold could not be used, because there is a small fiber loss through the wire during the sheet-forming operation.

The possibility of forming the handsheets on a filter pad in a Buchner funnel was considered but with the coarse fractions of a pulp it was found difficult to obtain good formation by the use of such a procedure. The suggestion that sheets be formed on a silk cloth placed over the wire of a British sheet mold was followed and it was found that this procedure gave good results. A test was made to see if there was any fiber loss in forming sheets in this manner. A thin pulp suspension was made up of fines from the spruce sulfite pulp. Equal volumes of this pulp suspension were filtered through (a) a filter paper of the type used in making pulp consistency tests and (b) a silk cloth placed over the wire of the British sheet mold. The pulp was agitated in the mold as in the regular sheet-forming operation with the same volume of water. The weight of the fines collected on the cloth was about 1 per cent less than that collected on the filter paper. This difference is so small that with the coarsest fractions of the pulp the loss would be negligible.

The cloth used was a fine grade of white silk. It was boiled in a soap solution to remove sizing and loading materials and was then thoroughly rinsed with water. After drying, the cloth was cut into squares about eight inches on a side.

In the sheet-forming operation the water leg of the sheet mold was filled with water and the silk cloth placed over the wire and carefully smoothed out. The sheet mold was closed and water added from the top, since it was not possible to force water up through the cloth without displacing it somewhat. Softened water

was used in the preparation of all the handsheets. The pulp sample was then added and agitated according to the standard procedure (TAPPI Standard T 205 m-40). The sheet was coughed off with a filter pad next to the sheet backed by two blotters. After removal from the wire of the sheet mold the silk cloth was carefully stripped from the handsheet. In all of the experiments except those otherwise designated a filter pad was placed on the wire side of the sheet so that the sheet was pressed and dried with a filter pad on both sides of the sheet. A metal plate was placed over the top filter pad as closely covering the handsheet as possible for the purpose of lining up the sheets for pressing and to aid in the storing of the sheets for drying. Both sides of the sheets thus formed had a matte surface rather than one glossy and one matte surface, as is the case of a handsheet pressed and dried with a metal plate in contact with one side. The reason for desiring a matte surface on both sides of a sheet was that such a sheet would be more homogeneous throughout its entire thickness than would a sheet with one glossy surface.

It was found that sheets could not be satisfactorily prepared from the fines by the above procedure because after formation they adhered to the cloth so strongly that they could not be removed. The handsheets from the fines and from all the fractions of the groundwood pulp were formed on a 6-inch Büchner funnel. A filter pad cut from blotting stock was used as a filtering medium to avoid the tendency for the pulp to collect over the holes in the Büchner funnel, which was observed when a thin piece of filter paper was employed. In forming a handsheet in the Büchner funnel the filter pad was placed

in the funnel, wet with water, and the suction applied lightly. The funnel was partly filled with water and the pulp added. The sides of the funnel should be tapped lightly to help distribute the pulp. After draining, the filter pad and sheet were removed from the funnel, a filter pad was placed over the sheet and the assembly pressed and dried.

All handsheets, with one exception, were pressed according to the standard procedure -- i.e., a five-minute pressing at 90 pounds per square inch pressure, followed by a change of blotters and a final pressing for two minutes at the same pressure as before. The spruce sulfite pulp used in several early experiments was pressed only five minutes.

D. MEASUREMENT OF OPTICAL PROPERTIES

As previously mentioned, the Kubelka-Munk equation affords a means of expressing the diffuse reflectance of a paper sheet in terms of two fundamental constants -- i.e., the scattering and absorption coefficients.

In Steele's derivation of the Kubelka and Munk equation (5) the general equation for the reflectance of an opaque pad of material is given as:

$$R_{\infty} = 1 + \frac{K}{S} - \left(\left(\frac{K}{S} \right)^2 + \frac{4R_0}{S} \right)^{\frac{1}{2}} \quad (1)$$

The general equation for reflectance of a sheet backed by a body of reflectance R_0 is:

$$\frac{R_1' = 1/R_0(R_1' - R_0) + R_0(R_1' - 1/R_0) + \frac{SX(1/R_0 - R_0)}{(R_1' - R_0) + (R_1' - 1/R_0) + \frac{SX(1/R_0 - R_0)}{}}}{(R_1' - R_0) + (R_1' - 1/R_0) + \frac{SX(1/R_0 - R_0)}} \quad (2)$$

where e is the base of natural logarithms; the other quantities are defined in the section, "Definition of Terms". Over a black background, $R_1' = 0$ and the above equation becomes:

$$R_0 = \frac{\frac{SX(1/R_0 - R_0)}{(1/R_0) + \frac{SX(1/R_0 - R_0)}{-R_0}}}{-1} \quad (3)$$

From equations (2) and (3) it is possible to evaluate the scattering power, SX , if two reflectance measurements are made. However, the solution of these equations is so difficult that it is impractical to work with the equation where many computations are involved. For this reason charts have been constructed from these equations to facilitate the calculation of SX . The Bureau of Standards reflectance-opacity chart is of particular value because it shows the interrelation between \bar{C}_{99} , R_0 and R_{∞} which are commonly measured quantities. This chart has values of R_0 as ordinates and values of \bar{C}_{99} as abscissae. The constant R_{∞} lines have positive slopes and the constant SX lines have negative slopes. Knowing the values of R_0 and R_{∞} for a paper sheet the SX value may be read from the chart.

The SX value is the scattering power of the sheet and is a pure number, having no units. For a given value of reflectivity the opacity depends upon the value of SX . Obviously the quantity SX depends upon the thickness of the sheet and therefore this quantity

is a sheet property. The scattering coefficient, S , is a property of the substance of the finished paper.

In the evaluation of S the SX value is divided by X , the thickness of the sheet. This gives the S value of the furnish as it exists in the sheet. However, in certain cases such an evaluation of S is rather meaningless. An example is a dry paper sheet, with a high bulk and a certain SX value, which is compressed to one half of its original thickness. (It is assumed that the compression is accomplished by a static pressure that does not effect the surface of the sheet in contrast to a shearing pressure, such as in a calendering operation, which would change the surface characteristics of the sheet.) With the dry sheet there should be no appreciable increase in fiber bonding upon compression and so the SX value of the compressed sheet should be very nearly the same as for the uncompressed sheet. The caliper is half as great and therefore the S value will have been doubled. This is explained by the fact that there are double the number of scattering particles per unit thickness in the compressed sheet. The fact that the S value of the furnish has been doubled in an operation that has not changed the opacity of the sheet shows that this evaluation of S is rather useless. If, in this case, the SX value had been divided by the basis weight of the sheet, the " S " value obtained per unit weight of the furnish would have been the same before and after compression. Such an evaluation of " S " would seem more meaningful, because the optical properties of the paper sheet were not changed by the compression. Such a procedure might be considered as not being strictly correct mathematically because X is

properly the thickness. However, the incorrectness arises in dividing SX by the basis weight and calling the result \underline{S} . Properly, if SX is divided by the basis weight, expressed as \underline{W} , the value $\underline{SX}/\underline{W}$ is obtained. This gives an expression of the scattering power per unit areal weight of sheet, which should be more useful in most cases than an expression for the scattering power per unit thickness.

It was decided to evaluate the scattering power of the pulps by this means. Since the quantity $\underline{SX}/\underline{W}$ should not properly be called the scattering coefficient, the designation of "Specific Scattering Coefficient" and the symbol \underline{S}' will be used for it. Corresponding to the value, \underline{S}' , will be the "Specific Absorption Coefficient", \underline{K}' , obtained by multiplying $\underline{K}/\underline{S}$ by \underline{S}' .

It is clear that the contribution of an individual component of a sheet to the total scattering power of that sheet is the product of the weight of the component in one ream area and its specific scattering coefficient. Thus,

$$SX = S'_1 W_1 + S'_2 W_2 + S'_3 W_3 + \dots$$

where $W_1 + W_2 + W_3 \dots = W$ Or,

$$\underline{S}' = SX/W = (S'_1 W_1 + S'_2 W_2 + S'_3 W_3 + \dots)/W$$

that is, the specific scattering coefficient of the sheet is the weighted average of the \underline{S}' values of the components. These formulas presume, of course, that reduction of scattering through internal bonding is negligible.

That the Kubelka-Munk equation is applicable in describing the optical characteristics of a paper sheet has been shown in t

following cases:

Judd (6) made measurements to determine if the Kubelka-Munk equation is valid in evaluating the optical properties of different types of paper. He concluded from his studies that, except for deviations less than one per cent, the equation does apply to paper. Steele (5) has demonstrated the value of the equation in evaluating the effects of filler in paper. Harrison (15) showed the applicability of this equation in measuring the retention of dyes in paper. Tongren (16) used the equation to study the discoloration of artificially aged papers. Nolan (17) used the equation in predicting the color of paper dyed with a combination of dyestuffs. Peete (7) evaluated the scattering and absorption coefficients of dyed hand sheets by use of the Kubelka-Munk equation. Davis (18) described the use of this equation in evaluating the optical properties of paper containing loading materials.

It is thus evident that the use of this equation in evaluating the optical characteristics of a paper sheet is fundamentally sound, and that its application has been proved in practical experiments.

The General Electric recording spectrophotometer was used to make reflectance measurements on the samples. This instrument has been discussed in detail by Hardy (19). By means of this instrument a reflectance curve for the sample could be obtained for all wavelengths of visible light from 400 to 700 mm wavelength. Carefully surfaced blocks of magnesium carbonate which were considered to have an absolute reflectance of 0.97 were used as standards for the

reflectance measurements. These blocks were checked against a scale of brightness which is standardized by means of freshly prepared surfaces of magnesium oxide; the particular supply of magnesium carbonate is unusual in possessing a reflectance equal to that of magnesium oxide, i.e., 0.97. For practical purposes reflectance values were taken only at a limited number of wavelengths -- viz, 420, 500, 600, and 700 nm.

In making the reflectance measurements the handsheets were cut into small tabs that would fit conveniently over the sample opening of the spectrophotometer. The reflectance measurements were those of R_p , for which the backing of the single sheet was a cavity lined with black velvet, and of R_{90} the reflectance of the sheet backed by an opaque pad of sheets. In general 10 samples were used in obtaining average values of these two reflectance measurements. The reflectance measurements were made with the light source incident on the top side of the sheet.

Thickness and basis weight measurements were made on inch-square specimens, which were cut from the tabs in such manner as to include as closely as possible the actual area illuminated in the reflectance measurements. These measurements were made on the entire number of tabs in the sample and the values divided by the number of tabs in order to obtain average values of the caliper and basis weight.

The average values of R_p and R_{90} were multiplied by 0.97 to obtain absolute reflectances and these values were used to obtain

the \underline{S} value from the Bureau of Standards reflectance-capacity chart. The \underline{K} value was then divided by the average value of the basis weight, \underline{W} , to obtain \underline{S}' . The basis weight was expressed in terms of pounds per 25 x 40 -500 ream. The value of $\underline{K}/\underline{S}$ was evaluated from the relation $\underline{K}/\underline{S} = (1-\underline{S}_0)^2/2\underline{S}_0$ which is another form of equation (1). The value of \underline{K}' was then obtained by multiplying $\underline{K}/\underline{S}$ by \underline{S}' .

5. AREA MEASUREMENTS ON PULP SAMPLES

The scattering coefficient of a pulp is influenced by such factors as particle size and shape, the degree of bonding between fibers, and the index of refraction of the fibers. The absorption coefficient is influenced to some extent by the degree of bonding between fibers and the index of refraction of the fibers, but to a much greater extent by changes in the bleaching or the dyeing of a pulp. The fractions of any one given pulp, with the exceptions of the fines, would be expected to have about the same degree of bonding between fibers when formed in a paper sheet, and also the index of refraction of these fractions should be nearly alike. Any changes in the scattering coefficient of the different fractions, with the exception of the fines, could then be explained by differences in the fiber dimensions. Any variation in the absorption coefficient of various fractions would be due in the most part to differences in the degree of purification of these fractions and would not have any direct relationship to the particle size.

It was therefore necessary to make some type of measurement of fiber size in order to have an index to explain variations in the

scattering coefficients of the different pulp fractions. If the scattering coefficient depended upon the fiber length alone, the measurement of fiber size would be relatively simple. It might be possible to obtain an approximation of the average fiber length of a given fraction in terms of the mesh size of the screen upon which the pulp fraction was retained. However, the scattering coefficient depends on fiber width as well as fiber length and even an accurate microscopic measurement of the fiber length would be of little value here.

Some type of area measurement for the different pulp fractions was thus necessary. A microscopic measurement of length and width could be used for this purpose. However, fibers vary widely in the shape of their cross sections and, therefore, this type of measurement is only approximately correct, because the shape of some of the fiber cross section must be assumed in calculating the fiber area.

A rapid method for the routine determination of the surface area of pulps is available through the "specific surface area measurement" as developed by Clark (20); modifications of the original procedure have been made by McWen (21).

In this method of area determination the fibers are coated with a uniform layer of silver and the area of this silver coating determined. The measurement of the area of silver coating depends upon the fact that hydrogen peroxide is catalytically decomposed when in contact with a silver surface. This reaction is presumably a first order reaction and a measurement of the rate of reaction will thus

give a measure of the total area of silver. The method adopted by Clark (20) for the measurement of the rate of reaction was to determine the amount of hydrogen peroxide decomposed by a silvered pulp sample in a definite time (100 seconds). In an attempt to obtain an absolute value for the surface area of fibers a calibration curve was made. The amount of hydrogen peroxide consumed in this determination when small squares of cellophane of known area were silvered and treated with hydrogen peroxide under the standard conditions of the determination was used as the basis for the construction of this calibration chart. A reproduction of this chart is shown in Figure 1. The construction of this chart is described by Clark (20).

The actual procedure used in the area determinations was the modified procedure as given by Nathan (21). In this procedure about 15 to 30 milligrams of fiber are silvered by treating with 100 cc. of a 1 per cent solution of ammoniacal silver nitrate at the boiling point. The silvering is carried out for a sufficient time to produce a uniform opaque layer of silver on the fibers. This length of time is roughly twice the time that it takes the pulp to go through a red color and turn black. The actual time of silvering for most of the pulps was about fifteen minutes. The fibers are then thoroughly washed with distilled water and transferred to a reaction flask together with 95 cc. of distilled water and 5 cc. of a borate buffer solution, prepared by dissolving 20 grams of hydrated sodium borate and 0.5 gram of sodium hydroxide in 500 cc. of water. The borate buffer solution is used to keep the pH of the reaction solution above 7. The contents of the flask

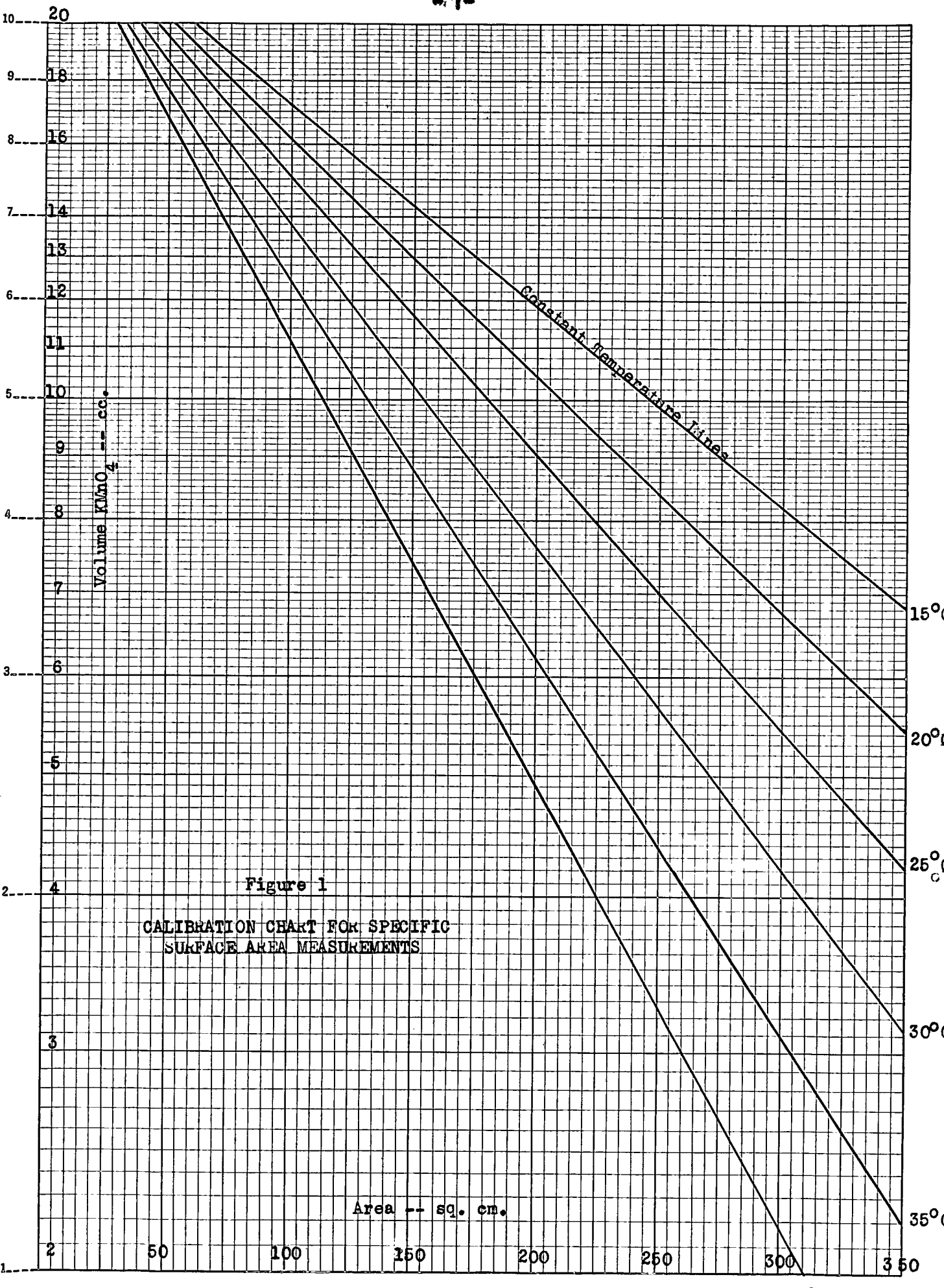


Figure 1
CALIBRATION CHART FOR SPECIFIC
SURFACE AREA MEASUREMENTS

Area -- sq. cm.

are stirred at a moderate speed by means of an electric stirrer. Twenty-five cc. of 0.5 N hydrogen peroxide are rapidly introduced and the timer started. At the end of 50 sec. the temperature of the reaction mixture is taken and at the end of 100 sec. the reaction is stopped by the rapid addition of 15 cc. of 2 N sulfuric acid. The excess hydrogen peroxide is immediately titrated with 0.5 N potassium permanganate solution. From the amount of this solution used in the back titration and from the temperature the area can be read off the chart. The weight of the fiber is known and, therefore, the area per gram of pulp can be calculated easily.

P. EFFECT OF BEATING ON OPTICAL PROPERTIES

One experiment was made to determine the effect of beating on the optical properties of a paper sheet. The spruce sulfite pulp was used in this experiment. Since the optical properties of a paper sheet would be affected by the probable increase in ash content of pulp when beaten in a laboratory beater or pebble mill, it was decided to carry out the refining treatment in a Ljungström mill. Treatment of pulp in such a mill offers the minimum of contamination to the pulp of any refining equipment available.

Ninety grams of dry pulp were soaked in water overnight (softened water was used throughout in this experiment). The pulp was then broken up in two liters of water with 75,000 revolutions in the British disintegrator. The disintegrated pulp was then thickened on a Disher funnel and divided into three 30-gram (oven-dry) portions. One of these 30-gram portions was then

dispersed in water in a total volume of one liter and the pulp suspension added to the mill. The mill was closed and run for the desired length of time -- 15, 30, and 60 minutes -- after which the pulp was removed and a volume of stock equivalent to 12.5 grams of oven-dry pulp was diluted to 2 liters and stirred for 7,500 revolutions in the British disintegrator. Freshness tests were made on the Schopper Riegler freshness tester.

The sheetmaking procedure varied from that described before in that the sheets were formed directly on the wire of the British sheet mold. The standard sheetmaking procedure (TAPPI Standard T 205 m-40) was used throughout with the following exceptions. One set of sheets was pressed with a filter pad in contact with both sides of the sheet so that both sides of the sheet had a matte surface. Another set of sheets from each interval was pressed with a filter pad in contact with the top side of the sheet and a metal plate in contact with the wire side of the sheet. This gave a sheet with one glossy and one matte surface. The purpose of this was to show the effect of a glossy surface on the optical properties.

One experiment was made to show the effect of variations in wet pressing pressures on the optical properties of a paper sheet. The spruce sulfite pulp and the alpha pulp prepared from it were used in this experiment. Ninety grams (oven-dry weight) of each of these pulps were soaked in water overnight and disintegrated with 25,000 revolutions in the British disintegrator in two liters

of water. The sheets were formed directly on the wire of the British sheet mold by the standard procedure. In pressing these sheets a filter pad was placed in contact with both sides of the sheet. The pressing was carried out for five minutes, followed by a change of blotters, and another pressing for two minutes at the same pressure as before. The following pressures were used in the pressing of these sheets: 10, 50, 200, and 5000 pounds per square inch.

PRESENTATION AND DISCUSSION OF RESULTS

A, K' AND S' VALUES OF DIFFERENT PULP FRACTIONS

The specific scattering and absorption coefficients were evaluated for the fractions of six different pulps. These pulps and the numbers used in their designations are as follows:

<u>Fraction</u>	<u>Type of Pulp</u>
5 & 6	Bleached spruce sulfite
7	Bleached poplar sulfite - dry lap
9	Bleached hardwood soda
10	Fullly bleached jack pine kraft
11	Lightly bleached jack pine kraft
12	Spruce groundwood

The mesh size of the screen upon which the various fractions of the pulps were retained was used to designate these fractions. For example, Fraction 6-20 would refer to that portion of the bleached spruce sulfite pulp that was retained on the 20-mesh screen of the classifier. As explained before, the portion of the pulp passing through the 150-mesh screen of the classifier was referred to as "fines."

1. Screen Retention of Pulp

The screen retention of the various pulps is shown in Table I.

TABLE I
SCREEN RETENTION OF PULPS

Sample	On 20 mesh %	On 35 mesh %	On 65 mesh %	On 150 mesh %	Fines %
5	70.9	12.2	1.04	3.82	3.00
6	70.8	12.5	7.66	4.18	4.82
7	7.54	34.0	11.0	14.8	12.7
9	4.33	23.7	41.5	9.45	21.1
10	66.0	18.2	8.47	2.27	3.10
11	68.0	17.4	7.60	3.40	3.60
12	0.52	10.1	20.9	21.2	47.3

2. Composition of Various Handsheets

In general, the method of measuring the optical constants of the different pulp fractions was to prepare three handsheets from each fraction and make the necessary measurements on these. In addition to this, handsheets were prepared from mixtures of the various fractions. This was done to determine if the K' and g' values of a pulp fraction are the same when used alone as when mixed with other pulp fractions. In general, these fractions were mixed in proportions that were the same as in the original pulp.

Samples labelled "O" were made up from the original unfractionated pulp. Samples labelled "A" were made from all the fractions recombined to approximate the original. Table II shows the composition of the other mixtures of pulp fractions.

TABLE II

COMPOSITION OF SAMPLES PREPARED BY MIXING
TWO OR MORE FRACTIONS

Sample	Fraction				
	20 %	35 %	65 %	100 %	Fines %
1	74.6	12.8	8.46	4.04	0.0
2	85.0	15.0	0.0	0.0	0.0
3	90.0	0.0	0.0	10.0	0.0
4	0.0	51.2	32.8	15.9	0.0
5	0.0	60.0	0.0	0.0	40.0
6	0.0	80.0	0.0	0.0	20.0
7	5.48	30.0	52.5	12.0	0.0
8	0.0	0.0	30.0	0.0	10.0
9	0.0	0.0	60.0	0.0	40.0
10	0.0	0.0	30.0	0.0	70.0
11	69.5	19.2	2.9	2.4	0.0
12	70.6	18.1	7.9	3.5	0.0

I. Optical Constants of Different Pulp Fractions

The values of K_s , K_a , S_s , S_a , S' and K' for the different pulp and pulp fractions at four different wavelengths of the visible light spectrum are shown in detail in Table XIII in the Appendix.

B. ADDITIVE PROPERTY OF K' AND S'

Table III contains data on the specific scattering and absorption coefficients of different mixtures of pulp fractions at two different wavelengths. The values labelled "Obs." are the values actually obtained for handsheets made from the various combinations of pulp fractions. The values labelled "Calc." are those obtained by taking the K' or S' value for each fraction of pulp in the mixture, multiplying this value by the percentage of that fraction in the mixture, adding together the products thus obtained for each

fraction, and dividing by 100.

TABLE III

TEST OF THE ADDITIVE PROPERTY OF S' AND K'

Sample	300 mμ				600 mμ			
	$S' \times 10^4$		$K' \times 10^6$		$S' \times 10^4$		$K' \times 10^6$	
	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.	Obs.	Calc.
5-A	570	574	639	1274	541	542	483	978
5-B	581	582	458	443	550	551	339	314
5-C	563	566	427	404	535	536	316	283
5-D	571	575	450	456	541	545	333	327
6-A	669	653	577	567	635	614	432	425
6-B	624	609	567	737	586	576	366	470
7-A	634	566	814	1081	598	538	517	734
9-A	856	850	2070	3022	835	814	1040	1478
9-B	768	775	1755	1700	733	744	758	732
10-A	391	402	1350	1346	371	385	716	761
10-B	479	416	1140	1020	409	397	565	515
11-A	416	413	2640	2640	391	392	1000	1160
11-B	420	422	2530	2473	385	401	1020	1013
12-A	—	—	—	—	903	1023	3490	4270
Mixture A	479	480	1210	1533	468	459	693	729
" B	489	481	475	395	499	454	330	357
" C	835	789	4170	3703	775	747	2380	1999
" G'	704	789	4520	3703	669	747	2710	1999

Mixture A was a 50-50 mixture of bleached spruce sulfite and the lightly bleached kraft.

Mixture B was a 50-50 mixture of bleached spruce sulfite and alpha pulp.

Mixture C was a 50-50 mixture of bleached spruce sulfite and groundwood. This gave a two-sided sheet. C and C' refer to the same sheet with the reflectance measurements made with the light incident on the top and the wire side of the sheet, respectively.

The above data show that, in general, there is a good agreement between the observed and calculated value of S' and K' of a mixture of pulp fractions. In the case of samples containing fines this agreement was not very good in some cases, particularly

in sample 5-A and 7-A. Sample 7 is a hardwood pulp and contained a large percentage of fines. This may have caused a two-sided sheet or the fines may have had different $\underline{K'}$ and $\underline{S'}$ values when in a sheet alone than when mixed with other fractions. In the case of pulps containing small quantities of fines, particularly the two kraft pulps (samples 10-A and 11-A), it is seen that there is good agreement between the calculated and observed values of $\underline{K'}$ and $\underline{S'}$.

The agreement between the observed and calculated values of $\underline{K'}$ and $\underline{S'}$ is not so good in the case of the groundwood. This is perhaps explained by the fact that the measurements of $\underline{K'}$ and $\underline{S'}$ on the groundwood were the least accurate of those for any of the pulps; the groundwood sheets were so opaque that there was very little difference between the reflectance curve of a sheet backed by a black body and that of a sheet backed by a thick pad of sheets.

The purpose of the measurements on the mixtures of bleached sulfite with the lightly bleached kraft and the alpha pulp was to study the effect of differences in the degree of bleaching or in the refractive index of pulps upon the additive properties of $\underline{S'}$ and $\underline{K'}$. Kanamaru (22) has shown that the double refraction of cellulose fibers increases with the degree of removal of noncellulosic materials from the fibers. The caustic used in the preparation of the alpha pulp should have caused at least a small change in the double refraction of the fibers. The data obtained show that the observed and calculated values of $\underline{S'}$ for mixtures of these different pulps agree within about two per cent, but the agreement between the two

values of K' is not as good as this.

Leaving out the occasional abnormality which occurs in a sheet containing a large proportion of fines, it is apparent from the above data that, when pulp fractions are mixed, the K' and S' values are additive. This is true apparently for mixtures of fractions of one given pulp or for different types of pulps providing the sheet is homogeneous. In the case of the sheet made from the mixture of groundwood and sulfite pulps it is seen in Table XIII that the reflectivity with the wire side towards the light source is less than when the top side of the sheet is towards the light. This would indicate that there was a greater proportion of groundwood in the wire side of the sheet. This caused a nonhomogeneous sheet and gave a substantial difference in S' and K' depending upon which side was exposed to the light in the reflectance measurements.

1. Calculation of K' and S' Values of Fines by Difference

The fines from certain pulps, particularly the two kraft pulps and the poplar sulfite pulp, had very low specific scattering coefficients and high specific absorption coefficients. The fines from these pulps gave very dense sheets; those from the two kraft pulps closely resembled glassine. The strong fiber-to-fiber bonding associated with these dense sheets would account, in part at least, for the low S' values of the fines from these pulps. If the degree of bonding between the fines was greater when the fines were alone than when they were in a sheet with other fractions of pulp, this would explain partially the discrepancy between the observed and

calculated values of some of the mixtures of pulp fractions.

Certain mixtures of pulp fractions were made up to provide a means of calculating the $\underline{K'}$ and $\underline{S'}$ values of the fines by difference. These mixtures were combinations of the fines with one coarser fraction, and included Samples 7-B, 7-C, 9-C, 9-D, and 9-E which were made up with the proportions as given in Table II. In addition the $\underline{K'}$ and $\underline{S'}$ values could be calculated by difference from the values for the "A" samples since these samples, as explained before, were made up to approximate the original pulp and, therefore, contained fines.

In Table IV are shown observed $\underline{S'}$ and $\underline{K'}$ values of the fines from certain of the pulps and values for these coefficients as calculated by difference. This calculation is the reverse of the method used in obtaining the calculated values of $\underline{S'}$ and $\underline{K'}$ for the mixtures.

These data show that, for Pulp 7, the fines evidently were behaving different optically when alone than when in a sheet with other fractions. This is shown by the fact that all calculated values were higher than the observed value of $\underline{S'}$ for the fines when in a sheet alone. However, in the case of Sample 9 and 11, it is seen that the $\underline{S'}$ value of the fines is appreciably the same whether they are alone or mixed with other fractions of pulp. The data for Pulps 9 and 11 show quite clearly that the $\underline{K'}$ value of the fines is much less when the fines are mixed with other fractions than when the fines are alone. This may be due to a two-sided effect that

TABLE IV

Sample	$R' \times 10^4$ at 600 m μ .	$K' \times 10^6$ at 600 m μ .
7-fines		
Observed value	436	3980
Calculated value		
Sample 7-B	770	5270
Sample 7-C	900	4520
Sample 7-A	940	2270
9-fines		
Observed value	1080	7390
Calculated value		
Sample 9-C	1350	1550
Sample 9-D	1150	2170
Sample 9-E	1160	4940
11-fines		
Observed value	135	5000
Calculated value		
Sample 11-A	140	665

might occur in the case of a sheet that contains fines. This effect is discussed under another heading. There is a possibility of some sort of a "hiding" effect which would tend to obscure in part the absorbing power of the fines.

2. Effect of Two-Sidedness in a Sheet on Optical Properties

The effect of two-sidedness has been noted before in the case of the mixture of groundwood and sulfite pulps. It is also apparent that a two-sided effect might occur in sheets containing a large amount of fines. In the case of Sample 7-A there were discrepancies between the observed and calculated values of R' and K' . It was thought that this might be due to a two-sided effect, because this sample contained a relatively large proportion of fines. Reflectance measurements were made on either side of a tab

from this sample, but the difference in these measurements was too slight to be considered. However, in Samples 7-0 and 9-0 a slight two-sided effect was noticed. These two samples contained 20 and 10 per cent of fines, respectively. The data for these two samples, together with data for the groundwood-sulfite sheets, are shown in Table V.

TABLE V
EFFECT OF TWO-SIDEDNESS ON OPTICAL PROPERTIES OF A PAPER SHEET

Wavelength — 500 mm

Sample	<u>Top of sheet towards light</u>			<u>Wire side of sheet towards light</u>		
	R_{∞}	$S' \times 10^4$	$K' \times 10^6$	R_{∞}	$S' \times 10^4$	$K' \times 10^6$
7-0	0.778	625	1970	0.772	592	1990
9-0	0.806	885	825	0.803	860	830
Groundwood sulfite mixture	0.730	835	4170	0.700	704	4520

Since the top side of the sheet in each case had the higher reflectivity it would be expected that the wire side of the sheet would contain the larger proportion of the fraction having the lesser reflectivity. In the case of Sample 9-0 and the groundwood-sulfite mixture, the fraction having the less reflectivity also had the highest $\underline{S'}$ values. It would be expected then that the higher measured values of $\underline{S'}$ and $\underline{K'}$ would be obtained when the wire side of the sheet was incident to the light source in the reflectance measurements. The data show that this holds for $\underline{K'}$ but not for $\underline{S'}$. This

contradiction presumably arises from the fact that the Kubelka-Munk equation is not strictly valid when used with a nonhomogeneous sheet such as a two-sided sheet.

It is to be noticed that even with a sheet containing 20 per cent of fines, as in sample 7-0, the differences in \bar{S}^1 and \bar{K}^1 as measured on either side of the sheet are not large enough to explain discrepancies between calculated and observed values of \bar{S}^1 and \bar{K}^1 for sheets containing fines.

C. VARIATION OF \bar{S}^1 WITH SURFACE AREA

In Table VI are given values for the apparent density, \bar{S}^1 values, and \bar{K}^1 values of sheets made from the different pulps and pulp fractions together with the surface area of these pulps and fractions.

TABLE VI

<u>Sample</u>	<u>Apparent Density*</u>	<u>Surface Area sq. cm./g.</u>	<u>$\bar{S}^1 \times 10^4$</u>	<u>$\bar{K}^1 \times 10^6$</u>
6-0	8.94	13,000	582	330
6-20	8.30	10,600	528	241
6-35	8.36	13,900	601	294
6-65	8.65	15,200	670	306
6-150	8.83	15,400	697	302
6-fines	9.36	44,000	966	4530
7-0	9.78	14,340	589	509
7-20	9.66	12,700	465	318
7-35	9.47	13,300	484	206
7-65	9.48	15,900	555	272
7-150	10.3	17,900	646	352
7-fines	12.1	29,500	486	3980

* The values for apparent density were obtained by dividing the basis weight (pounds per 25 x 40 inch ream) by the caliper in mils.

next
page
also

TABLE VI - Continued

Sample	Apparent Density	Surface Area sq. cm./g.	$S' \times 10^4$	$K' \times 10^6$
9-0	7.78	20,900	829	818
9-20	6.75	8,700	452	653
9-35	6.00	14,600	641	684
9-65	7.31	18,300	783	748
9-150	8.60	23,900	955	867
9-fines	9.17	32,200	1080	9590
10-0	11.0	15,900	401	646
10-20	10.6	17,900	380	490
10-35	11.2	16,200	422	536
10-65	11.6	17,700	454	573
10-150	12.4	19,300	495	787
10-fines	17.4	38,000	138	5360
11-0	11.3	14,900	384	960
11-20	10.5	12,600	388	992
11-35	11.2	15,600	413	1020
11-65	11.8	18,200	442	1080
11-150	12.2	20,900	476	1230
11-fines	17.2	38,400	155	5090
12-0	7.14	34,200	271	2770
12-20	4.96	11,400	432	2180
12-35	5.52	12,500	522	1920
12-65	5.91	13,900	634	2160
12-150	6.69	24,100	766	2680
12-fines	8.66	47,400	1430	6590
Alpha pulp	7.1	-----	383	286

Davis (18) has stated that the scattering coefficient should be proportional to the surface area per unit mass of the material. On the basis of this statement it was considered of interest to plot the S' values against the surface area of the different fractions and study the resulting curves.

The curves for the two sulfite pulps are shown in Figure 2, those for the remaining pulps in Figure 3. It is seen that the

Figure 2.

Variation of S' with Fiber Surface Area

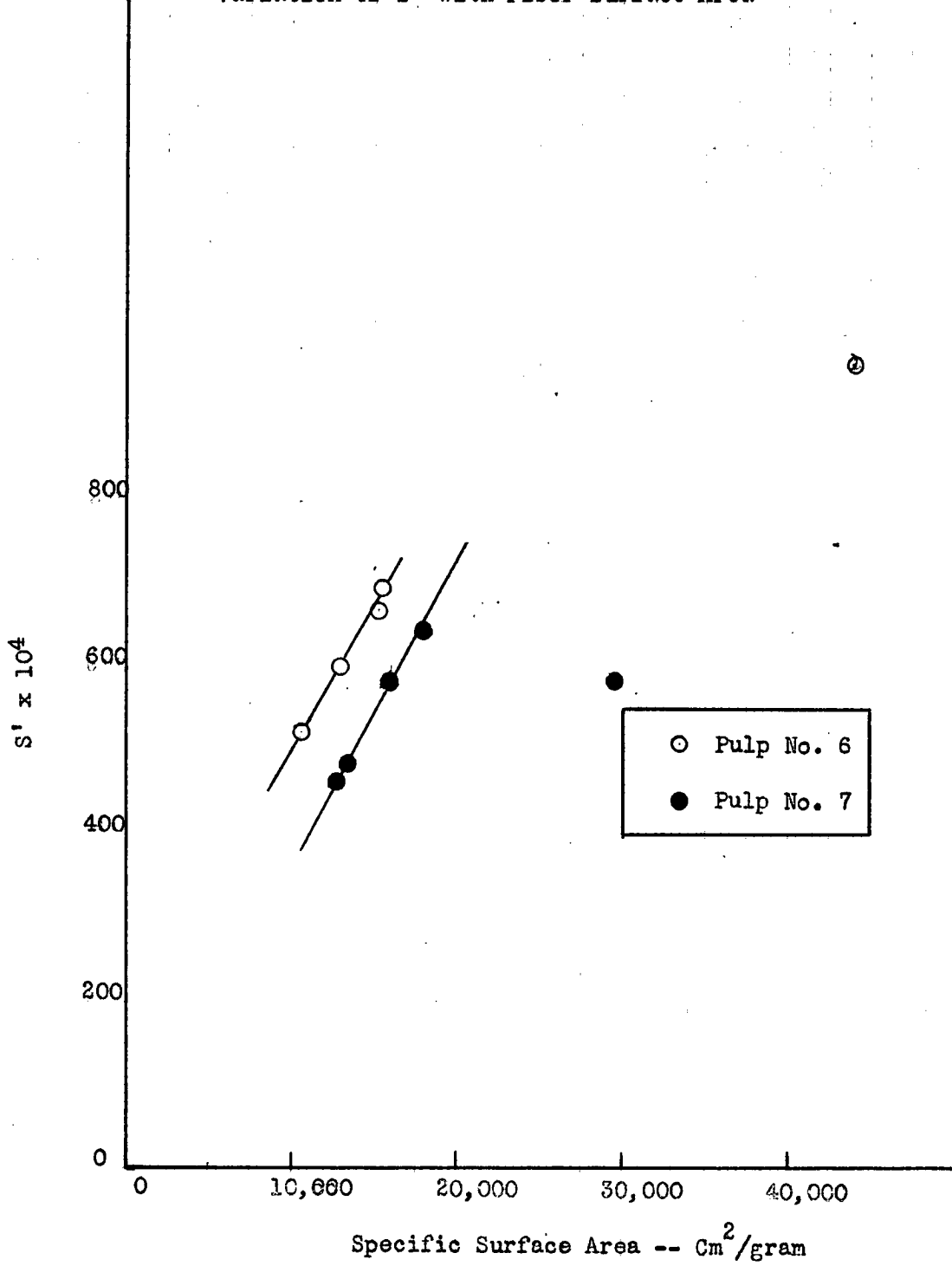
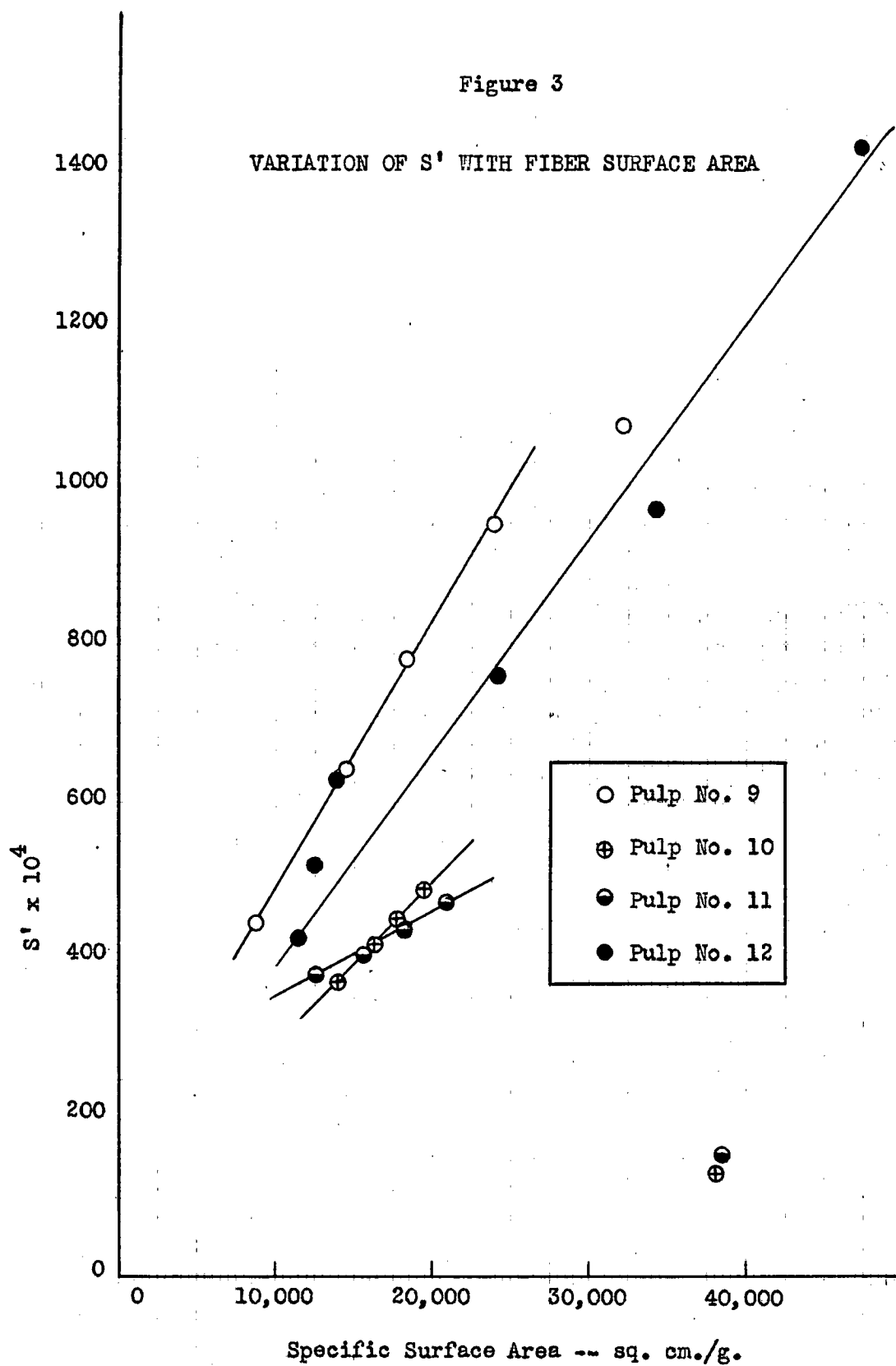


Figure 3



values for all fractions of any one pulp, with the exception of the fines fall on the same straight line. A criticism might be directed at drawing a straight line through the points for all the pulp fractions with the exception of the fines and not allowing the value for the fines to influence the shape of the curve. However, cognizance of the nature of the sheets made from the fines justifies the construction of the curves as shown in the two figures.

The data for the groundwood samples are the least accurate of any obtained. One reason for this is the difficulty of obtaining accurate $\underline{S\bar{K}}$ values because of the small difference between \underline{K}_0 and \underline{K}_∞ for the rather opaque sheets formed from the finer fractions of the groundwood. Also, it was difficult to obtain accurate area measurements on the fine fractions of groundwood because of the tendency of these fractions to lump together. The curve for the groundwood fractions may be slightly misplaced but in consideration of the above it would seem proper to draw a straight line through the points for the groundwood fractions as was done for the chemical pulps.

It is seen in the case of the fines from the groundwood that the point fell on the curve, whereas the corresponding point for the other pulps was usually far from the curve. This is apparently to be explained by the fact that the fines of groundwood are quite different from those of a chemical pulp. In groundwood the fines are made up of a fine material or debris which is the result of comminution in the grinding operation and which has no definite structural form. The fines from a chemical pulp contain some structureless debris

resulting from mechanical treatment of the fibers, but they also have a large proportion of the ray cells of the wood. It is possible that, in the fines from a chemical pulp, a different substance optically is present than in the case of the coarse fractions of the pulp. Ritter and Mitchell (21) have published data showing that the ray cells of basswood holocellulose behave differently in polarized light than do the fibers. The vibration plane of the slow-light component of fibers is parallel to the long axis, whereas the opposite is true in the case of the ray cells. Fines containing a large proportion of ray cells, therefore, might behave differently than the coarse fractions of a pulp. This would account, in part, for the very low S' values of the fines from the kraft pulps, although it is equally possible that this is due to the high density of sheets formed from these fines.

In addition to the above, it should be noted that the fines from groundwood formed a sheet that differed little from those prepared with the other fractions. In the case of the chemical pulps the sheets made from the fines were usually "tinny" and brittle.

It is seen that the slopes and height of the curves for the various pulps are quite different. It would be reasonable to believe that these differences are caused by variations in the sheet density of the different fractions but analysis of the data disproves this. For example, the groundwood fractions have the lowest density of any of the pulp fractions and hence for a given

surface area it would be expected that they would have the highest specific scattering coefficients. The data, however, show that for a given surface area the groundwood has a lower S' value than either the spruce sulfite or the hardwood soda pulps.

In the case of the chemical pulps it was thought that it might be possible to develop an empirical relation between fiber area, sheet density, and the scattering coefficient. By using a relation of the type

$$S' = k (d)^n A$$

where k = a constant, S' = specific scattering coefficient, and
 n = a constant, A = surface area,
 d = apparent density,

it was possible to find values of k and n that would satisfy the data for all fractions of any one pulp except the fines. However, when the formula with the constants obtained for one pulp was applied to another pulp the values of S' calculated from the surface area and density did not agree with the observed values. More complex empirical relations were tried but the results were no better. It is evident that conclusions to be drawn from the slope and height of the curves will have to be qualitative.

From a study of the curves and the data on apparent densities of the pulp fractions it is apparent that, in general, the greater the increase in apparent density with increasing surface area, the less steep the slope of the curves. Samples 10 and 11, in particular, show rapid increases in apparent density with increasing surface area and it is these samples which have the curves

of least slope. The fractions of Sample 11 show a slightly larger increase in apparent density with surface area than do the fractions of Sample 10, and it is seen that the curve for Sample 11 has a lesser slope than that of Sample 10. These results are what would be expected, for with increased sheet density there occurs a lowered value of \underline{S}' .

The fact that groundwood has the lowest sheet density of any of the pulps, which would tend to give it a very high specific scattering coefficient per unit surface area, together with the fact that it has a lower scattering coefficient per unit surface area than either the soda or the spruce sulfite pulps, might be used as a basis for reasoning that in the pulping of wood changes occur in the fiber structure which increase the scattering coefficient of the fibers. Such changes would be discontinuities in the fiber structure, or changes in the double refraction as mentioned by Kanazawa (22), caused by the removal of inkrustants during the cooking process. Such reasoning assumes that some scattering of light is taking place on the interior of the fibers which may, or may not, be the case. However, such reasoning, while very plausible, cannot be carried too far. The alpha pulp should be almost free of inkrustants and yet it has a very low scattering coefficient per unit of surface area.

The opacity of a pulp is related to both the \underline{K}' and \underline{S}' values. Except for the fines, the \underline{K}' values of the various fractions of groundwood were nearly alike. Probably the fines had

picked up some dirt in the fractionation for their specific absorption coefficient is very high compared with that of the original pulp. Since the scattering coefficient is seen to be a linear function of the surface area, it is apparent that, except for a displacement due to a possible high absorption coefficient of the fines, the opacity of the groundwood is a direct function of the surface area. This same reasoning holds true within limits for the chemical pulps, but in these cases there is no opportunity to vary the particle size as can be done with groundwood. Table VII gives values of the surface area of the groundwood and printing opacity values at 600 mm wavelength obtained by dividing R_p by R_∞ for this wavelength.

TABLE VII

RELATION OF SURFACE AREA TO OPACITY FOR GROUNDWOOD FRACTIONS

Wavelength -- 600 mm

<u>Fraction</u>	<u>Surface Area</u> sq. cm./g.	<u>$\frac{R_p}{R_\infty}$</u>
12-20	11,400	79.8
12-35	12,500	83.0
12-65	13,900	87.4
12-150	24,100	91.1
12-Fines	47,400	98.8
12-0	34,200	92.6

The preceding data clearly show the high opacity obtained with the fine fractions of groundwood.

D. EFFECT OF USING DRIED PULP ON THE OPTICAL PROPERTIES OF PAPER

One experiment was carried out to illustrate the effect on optical properties of drying a pulp. The bleached poplar sulfite pulp was available both in wet lap and in air-dry form.

The data for Sample 7-0 serve as the results for the air-dry pulp. A sample of the wet-lap pulp was disintegrated and formed into sheets in exactly the same manner as were the sheets from the dried pulp. The necessary reflectance and basis weight measurements are shown in Table VIII.

TABLE VIII

DIFFERENCES IN OPTICAL PROPERTIES OF SHEETS
FORMED FROM DRIED AND WET-LAP PULP

Wavelength -- 600 mm

Sample	Basis Weight 25 x 40 - 500	Apparent Density	E_0	E_{∞}	$S' \times 10^4$	$K' \times 10^6$	E_0/E_{∞}
Sheet Formed From Wet Lap Pulp	46.7	12.8	0.654	0.846	432	605	77.3
Sheet Formed From Dried Pulp	44.2	9.56	0.710	0.877	589	509	81.0

The greatly increased value of β' for the dried pulp is apparent. The sheets formed from the dried pulp had a substantially lower density than those formed from the wet-lap pulp. This means that the dried pulp had poorer bonding qualities than the wet-lap

pulp, and presumably this is the only reason for the higher $\underline{S'}$ value of the dried pulp. The $\underline{K'}$ value for the sheet made from the wet-lap pulp is seen to be higher than that of the sheet formed from the dried pulp. This is perhaps owing in part to the increased density of the former sheets; but is more likely caused almost entirely by a reversion in brightness of the wet-lap pulp. This reversion is shown by the low \underline{R}_0 value of the sheet formed from the wet-lap pulp as compared with the \underline{R}_{20} value of the sheet formed from the dried pulp.

The ratio of \underline{R}_0 to \underline{R}_{20} is taken as a measure of the opacity of the two types of sheets. The opacities of the two sheets are not directly comparable because of their difference in basis weight. The sheets formed from the dried pulp had the lower basis weight and, had the opacity values been corrected to the same basis weight, it would have made the difference in the opacity values of these two types of sheets greater than that indicated in the table. The increase in $\underline{S'}$ and opacity resulting from using pulp that had simply been air-dried is surprising. This increased opacity illustrates clearly the reason for using dry-lap pulp or dry broke to impart opacity to a paper sheet.

E. EFFECT OF BEATING AND VARIATION IN PRESSING ON OPTICAL PROPERTIES OF PAPER

Studies on the effect of beating on the optical properties of a paper sheet have been made by Probst (5) and Foote (7). However, it was felt that a study of the effect of beating on the optical properties of one of the pulps used in this investigation should be made. Bleached spruce sulfite pulp was used in this experiment. The

zero interval was pulp that had been given a disintegration consisting of treatment in the British disintegrator with 25,000 revolutions. The results of this experiment are shown in Table IX.

TABLE IX
EFFECT OF BEATING ON OPTICAL PROPERTIES

Optical measurements at 600 mμ					
Beating Interval — min.		0	15	30	60
Freeness — cc. S. R.		835	690	520	395
Surface Area — sq. cm./g.		11,900	12,700	13,300	16,000
Sheets A	Apparent Density	—	14.0	15.8	17.0
	R_{∞}		0.880	0.853	0.824
	$S' \times 10^4$		364	303	248
	$K' \times 10^6$		298	384	466
Sheets B	Apparent Density	10.5	13.5	14.5	15.7
	R_{∞}	0.886	0.852	0.851	0.835
	$S' \times 10^4$	537	348	298	249
	$K' \times 10^6$	394	275	389	406

Sheets A were pressed with a metal plate in contact with one surface of the sheet giving a glossy surface, sheets B were pressed with a filter pad in direct contact with both sides of the sheet so that they had a matte surface.

It is seen from the above data that substantial decreases in S' occur with increased beating. The data show an initial decrease in K' in the first stages of beating, followed by an increase. The effect of the glazed surface in giving increased values of S' is rather surprising. The magnitude of this difference in S' is not

large, but the same effect was noted to a greater extent in a preliminary experiment on unbeaten pulp. The sheets with a glazed surface had a higher density than the others and, therefore, it would be expected that they might have a lower \underline{S}' value. That this difference may be due to lack of homogeneity in the sheet with the glazed surface is seen from the fact that this difference in \underline{S}' for the two types of sheets disappears with increased beating -- the \underline{S}' values for the two sheets at the 60-minute interval are nearly equal.

An experiment was also made on the effect of different degrees of wet pressing on the optical properties of a paper sheet. The methods used in forming handsheets for this experiment have been described. Two pulps were used: spruce sulfite and the alpha pulp prepared from it. The results are shown in Table X.

The results for the bleached sulfite pulp show a decrease in \underline{S}' with increasing apparent density which was observed also in the case of the beaten pulp. The results for the sheets labelled B in Table IX are comparable with the results in Table X because the sheets in both cases were prepared with a matte surface on both sides of the sheet. These data show that the sheets made from beaten pulp had lower \underline{S}' values than did sheets made from unbeaten pulp pressed to the same apparent density. The same initial decrease in \underline{K}' with increasing sheet density is shown to occur with increased degrees of pressing as was observed with increased degrees of beating.

The results for the alpha pulp show an initial increase in

TABLE X

EFFECT OF VARIATIONS IN THE DEGREE OF WET
PRESSING ON OPTICAL PROPERTIES

Wavelength -- 600 mμ

<u>Sample</u>	<u>Pressure</u> <u>lb./sq.in.</u>	<u>Apparent</u> <u>Density</u>	<u>R_o</u>	<u>$S' \times 10^4$</u>	<u>$K' \times 10^6$</u>
Sulfite	10	8.35	0.881	561	491
	50	10.5	0.886	537	394
	200	13.0	0.880	449	367
	5000	14.9	0.852	310	400
Alpha pulp	10	5.3	0.828	387	273
	50	7.2	0.891	401	268
	200	9.8	0.890	387	263
	5000	13.5	0.873	286	264

S' with the first increase in apparent density. This is rather unusual for there is no reason why the S' value should increase and is probably because of experimental error. After this apparent initial increase, the S' value fell off rapidly with increased apparent density. It was not expected that this rapid drop in S' would be observed, for this indicates a relatively high degree of bonding which would seem unusual with this type of pulp. Probst (S') has shown that a pulp of this type has very poor bonding qualities.

E. EVALUATION OF AREA OF OPTICAL CONTACT OF FIBERS

It has been shown reasonably well that, with the exception of the fines, the S' value of the different fractions of any one pulp is a linear function of the surface area of the fibers. This offers a basis for the evaluation of the area of optical contact between

fibers in a sheet. A given fraction of pulp has a certain $\underline{S'}$ value when formed into a sheet. Of the total area of this fraction only a portion contributes to the $\underline{S'}$ value, because part of the area of the fibers are in optical contact with other fibers in the sheet. If a sheet could be produced in which there was no fiber bonding, there would be no fibers in optical contact and it could be assumed that all of the area of the pulp contributes to the $\underline{S'}$ value. If the $\underline{S'}$ value of the fibers in such a sheet were known, it should be possible from these $\underline{S'}$ values and the areas of other pulp fractions that are bonded together when in a sheet, to calculate a value for the area of the fibers that is in optical contact.

It was first necessary to form a sheet with no fiber bonding, which was done in n-butyl alcohol. This has been shown by Kress and Bialkowski (24) to have practically no swelling action on cellulose fibers and presumably there should be no fiber-to-fiber bondings in a sheet formed from pulp fibers in this medium.

Spruce sulfite pulp was broken up in water in the British disintegrator for 25,000 revolutions. A small portion of this pulp was then treated with acetone several times to remove as much water as possible. The pulp was then treated repeatedly with butyl alcohol and finally allowed to stand overnight in the alcohol, after which it was pressed out and dispersed in fresh butyl alcohol. The sheets were formed on a piece of wire from a British sheet mold out to fit a 6-inch Michner funnel. It was possible to obtain a fiber mat that would hold together well enough to be conched off onto a

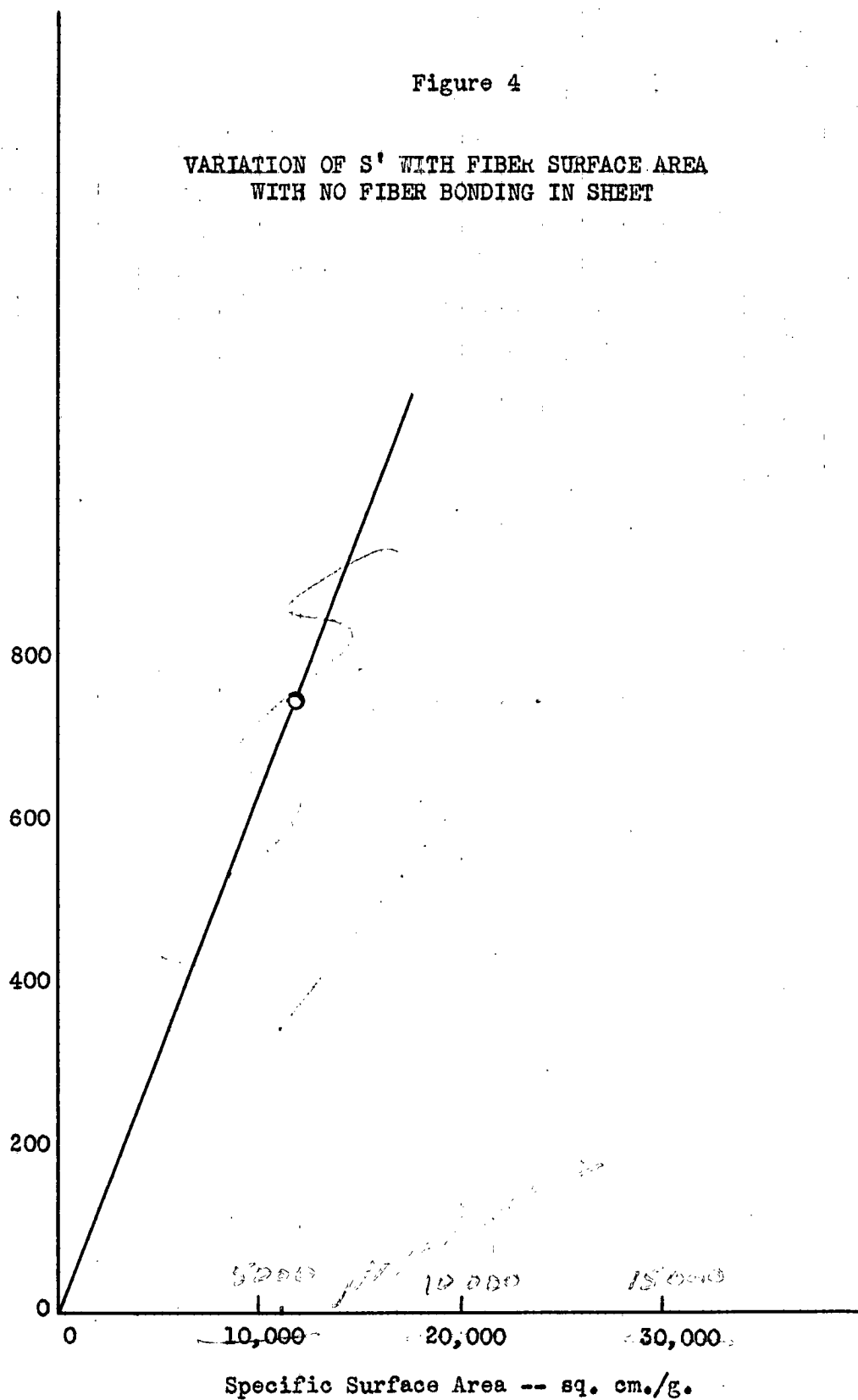
filter pad. The formation was very poor, however, and a quantity of sheets had to be prepared in order to obtain enough reflectance measurements to permit an accurate evaluation of \underline{g} . The sheets were pressed at 50 lb./in.² pressure for 7 minutes with a filter pad in contact with each side of the sheet.

The curve showing the relation between the \underline{g} ' value and the surface area of fractions of the spruce sulfite is a straight line which does not pass through the origin. The results for some of the other pulps, the poplar sulfite pulp in particular, indicate that if all fractions of a pulp had the same density this curve should pass through the origin.

The \underline{g} ' value of this pulp under the conditions of no fiber bending was 790×10^{-4} at 600 mm wavelength. The area of the sulfite pulp was 11,900 square centimeters per gram of pulp. This area measurement was made on a sample from pulp that had been formed into a sheet on the sheet mold. This was done to allow for the loss of fine material through the wire. These values give one point on a curve of \underline{g} ' against surface area. From the above reasoning this curve should pass through the origin. A straight line was therefore drawn from this point to the origin and this curve (Figure 4) used in evaluating area of optical contact. Taking the value of \underline{g} ' for the zero interval from Table IX, which is found to be 537×10^{-4} , a value of the area contributing to this \underline{g} ' value can be read off the curve. A value of 5700 cm.²/g. is obtained for the area contributing to the scattering coefficient, the actual area of the

Figure 4

VARIATION OF S' WITH FIBER SURFACE AREA
WITH NO FIBER BONDING IN SHEET



pulp as measured is 11,900. The difference between these two or 1200 is therefore the area in optical contact. This evaluation was carried out for the samples used in the beating experiment and also for the samples subjected to different degrees of wet pressing. The values obtained are given in Table XI.

TABLE XI

Sample	$S' \times 10^4$	Area contributing to S' from Figure 4 sq. cm./g.	Measured surface area sq. cm./g.	Area in Optical Contact sq. cm./g.	Percentage of area in Contact
Beater Samples					
0-interval	537	8500 5700	11,900	3400 3200	29 27
15 min.	348	5600	12,700	7100	56
30 min.	298	4800	15,300	10,500	69
60 min.	249	4000	16,000	12,000	75
Sulfite Pulp					
Pressure lb./sq.in.					
10	561	9000	11,900	2900	24
50	537	8700	11,900	3200	27
200	449	7200	11,900	4700	40
5000	310	5000	11,900	6900	58
Alpha Pulp					
Pressure lb./sq.in.					
10	387	6300	8800	2500	29
50	401	6500	8800	2300	23
200	387	6300	8800	2500	29
5000	286	4600	8800	4200	48

The above data clearly shows the large increase in the degree of bonding for a beaten pulp.

Outside of the anomalous behavior of the sheet made from

alpha pulp which was pressed at 10 lbs./sq.in., it is seen that, in the alpha pulp, the area of fiber in optical contact is much less than that in sulfite pulp for sheets pressed at the same pressure. Also, it is seen that the percentage of area in contact is less for the alpha pulp.

This method for the measurement of the optical contact of fibers is subject to criticism because of the assumptions made in the determination and, for this reason, the data in Table XI are presented with no claim as to its accuracy. However, this method has the possibility of being developed into a method of measuring the relative bonding areas of pulps, which could be of considerable value.

The surface area of the alpha pulp was evaluated on a sample from a sheet formed on the sheet mold. This was done in order to obtain an area measurement which would represent that of the fibers actually in the sheet. It is seen that the area of the alpha pulp is much less than that of the sulfite pulp from which the alpha pulp was formed. This observation indicates that the treatment of the alpha pulp has caused some basic change in the surface of the fibers. This change is presumably caused either by the dissolving off of any fibrillae (microscopic or submicroscopic) on the surface of the fiber, or by such fibrillae collapsing onto the surface of the fiber so that they are effectively removed in the area determination. The possibility exists, however, that the silver surface formed on the alpha pulp is of a slightly different nature

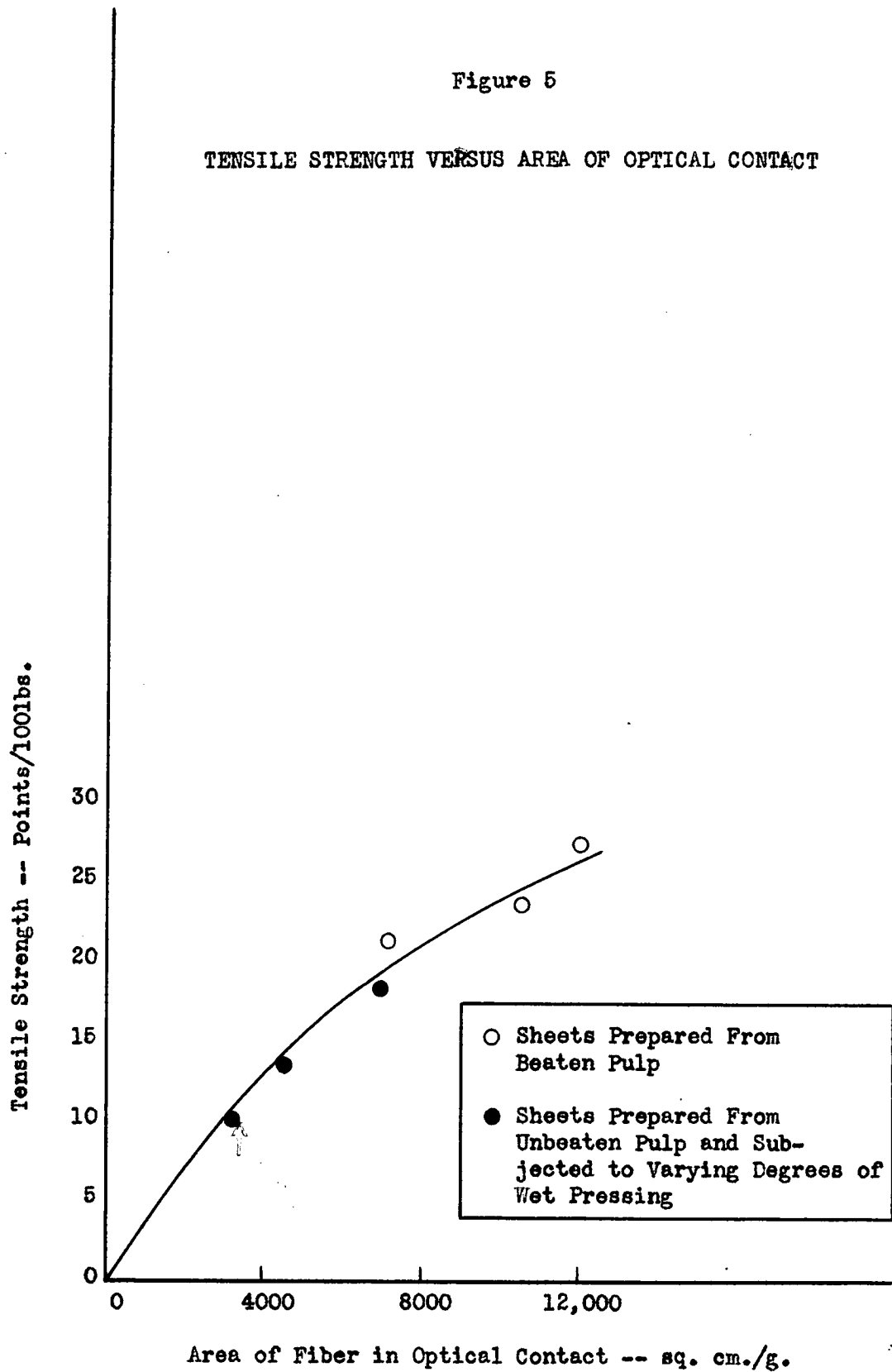
than that formed on the sulfite pulp. If this is so, it might account for some of the differences in the area measurement of the two types of pulp.

Relation Between Tensile Strength and Area of Fibers in Optical Contact

Tensile tests were run on the Schopper tensile tester for some of the handsheets prepared in the experiments on the effect of beating and variations in pressing on optical properties. Only a small amount of sample was available and the tests were run on strips one inch long. The data given in Table XII represent the results of these strength tests. The data for the alpha and sulfite pulps pressed at varying pressures are given to indicate the degree of strength to be realized by wet pressing, and to indicate that a considerable degree of strength can be developed with alpha pulp if pressed at sufficiently high pressures. Of particular interest is the comparison of the tensile strength of the beaten pulp samples with the calculated values for areas of optical contact as obtained from Table XI. The value for tensile strength in points /100 lbs. is obtained by dividing the tensile strength in pounds per sheet by the basis weight and multiplying by 100. In Figure 5 the tensile strengths of the sulfite pulp at various intervals of beating and varying pressing pressures are plotted against the calculated values of the area in optical contact for these samples. It is seen that the values for the sheets from unbeaten sulfite pulp pressed at 200 and 5000 lb./sq.in. fall approximately on the same curve as do the values for the beaten pulp. This indicates the relation

Figure 5

TENSILE STRENGTH VERSUS AREA OF OPTICAL CONTACT



between tensile strength and area of optical contact is the same whether the strength variations are obtained by beating of the pulp or by varying the degree of wet pressing of the sheets.

The shape of the curve in Figure 5 indicates a linear relationship between the area of optical contact of the fibers and the tensile strength during the first stages of beating. This is followed by a leveling off of the curve which is presumably due to a decreased fiber strength occasioned by beating. This decreased fiber strength would partially offset increases in strength caused by an increase in the area of optical contact.

TABLE XII

TENSILE STRENGTH OF HAND SHEETS

Pressure lb./sq.in.	<u>Tensile Strength</u> lbs.	<u>Basis wt.</u> 25-40-500 points /100 lbs.	<u>Tensile</u> <u>Strength</u>
Sheets from alpha pulp			
200	1.8	49.2	3.7
5000	3.6	54.6	6.6
Sheets from unbeaten sulfite pulp			
50	5.1	49.4	10.3
200	6.7	48.6	13.8
5000	8.7	46.7	18.6
Beaten pulp samples			
Zero Interval	5.1	49.4	10.3
15 min.	10.2	46.3	21.5
30 min.	10.9	45.7	23.8
60 min.	12.6	45.7	27.6

VII

CONCLUSIONS

1. Under the conditions of this work, a given fraction of pulp scatters or absorbs light independently of its surroundings -- i.e., the pulp fraction has the same specific scattering and absorption coefficient when mixed with other fractions as when alone.
2. In certain cases, the fines from a pulp do not give results which agree with the above observation. In most cases apparently, this discrepancy can be attributed to a two-sided effect produced by the presence of a large amount of fines in the sheet.
3. The specific scattering coefficient of the fractions of a pulp, with the exception of the fines, is a linear function of the surface area.
4. Different fractions of a pulp may give sheets of varying densities even when pressed under the same conditions. In general, the larger the surface area of a pulp fraction the greater its density, and the greater this variation in density with surface area, the less the slope of the curve of the specific scattering coefficient against surface area.
5. With a groundwood pulp the specific scattering coefficient of all fractions, including the fines, is a linear function of the

surface area. This indicates that, except for small changes in the absorption coefficient with surface area, the opacity depends directly on the fineness of the groundwood.

6. Groundwood has a lower specific scattering coefficient per unit surface area than any of the chemical pulps tested with a comparable sheet density. The higher specific scattering coefficient of chemical pulps with sheet densities comparable with those of groundwood is presumably caused by changes occasioned in these pulps by the pulping processes used. These changes may be in the nature of changes in the double refraction of the fibers or discontinuities in the fiber structure caused by the removal of inkrustants.
7. Sheets made from a dried pulp have a greater light scattering power and opacity than those formed from wet-lap pulp. This increased scattering power may be the result of the poorer bonding qualities of this pulp.
8. Increased sheet density, whether occasioned by beating of the pulp or by increased degrees of wet pressing, gives decreased values of the specific scattering coefficient. Increased sheet density apparently causes the specific absorption coefficient to first decrease to a minimum value and then to increase.

VIII

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APPENDIX

TABLE XIII

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength nm	R_p	R_∞	SX	$\frac{W}{25 \times 40 - 500}$	$\frac{S' \times 10^4}{}$	$\frac{K' \times 10^6}{}$
5-20	420	0.698	0.825	2.62	44.3	591	1096
	500	.702	.887	2.47		558	402
	600	.694	.903	2.33		528	275
	700	.680	.895	2.19		494	304
5-35	420	0.726	0.830	3.07	47.0	653	1140
	500	.732	.887	2.89		615	443
	600	.725	.900	2.75		585	325
	700	.712	.894	2.58		549	345
5-65	420	0.735	0.826	3.30	46.0	717	1316
	500	.742	.877	3.11		676	583
	600	.735	.890	2.92		635	432
	700	.724	.882	2.79		606	478
5-150	420	0.716	0.798	3.13	41.1	762	1950
	500	.728	.852	3.00		730	937
	600	.722	.864	2.82		687	735
	700	.711	.860	2.66		648	738
5-fines	420	0.309	0.326	1.50	26.6	563	39,200
	500	.364	.402	1.02		383	17,000
	600	.381	.436	1.03		377	13,700
	700	.378	.438	.95		357	12,900
5-0	420	0.683	0.769	2.72	43.5	625	2107
	500	.700	.841	2.58		593	890
	600	.694	.865	2.41		556	583
	700	.682	.859	2.28		524	606
5-A	420	0.690	0.794	2.66	43.7	609	1630
	500	.699	.861	2.49		570	639
	600	.692	.876	2.36		541	483
	700	.680	.870	2.23		510	495
5-B	420	0.709	0.824	2.81	45.7	615	1158
	500	.716	.882	2.66		581	458
	600	.707	.895	2.51		551	339
	700	.696	.889	2.38		521	361

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength mμ	R_s	R_∞	$\frac{R_s}{R_\infty}$ 25x40	$\frac{n}{D_{500}}$	$\frac{S \times 10^4}{D_{500}}$	$\frac{K \times 10^6}{D_{500}}$
5-0	420	0.701	0.821	2.67	45.8	582	1140
	500	.710	.884	2.58		563	427
	600	.703	.897	2.46		535	316
	700	.689	.888	2.31		504	356
5-D	420	0.704	0.820	2.74	45.2	605	1200
	500	.709	.882	2.58		571	450
	600	.701	.895	2.44		541	333
	700	.690	.892	2.30		509	332
5-2	420	0.731	0.820	3.25	46.1	704	1390
	500	.741	.877	3.09		669	577
	600	.735	.890	2.92		635	432
	700	.722	.884	2.75		596	452
6-20	420	0.703	0.823	2.70	45.3	596	1130
	500	.708	.892	2.53		559	366
	600	.700	.909	2.35		528	241
	700	.686	.890	2.26		499	340
6-35	420	0.726	0.820	3.14	47.1	667	1320
	500	.739	.890	3.01		639	435
	600	.732	.906	2.83		601	294
	700	.716	.882	2.66		565	446
6-65	420	0.742	0.821	3.49	45.1	775	1510
	500	.749	.893	3.18		706	452
	600	.743	.909	3.02		670	306
	700	.730	.890	2.86		634	431
6-150	420	0.729	0.788	3.62	45.2	801	2290
	500	.751	.864	3.37		746	798
	600	.747	.887	3.15		697	502
	700	.735	.879	2.98		660	550
6-fines	420	0.575	0.585	3.15	30.3	1040	15,300
	500	.649	.686	3.04		1008	7190
	600	.677	.737	2.93		966	4530
	700	.679	.755	2.76		911	3620

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength mm	n_D	n_{∞}	$\frac{2n_D - n_{\infty}}{25 \times 10^{-4}}$	$\frac{n_D - 1}{500}$	$\frac{2n_D - 1}{10^4}$	$\frac{n_D^2 - 1}{10^6}$
6-0	420	0.707	0.808	2.86	43.4	659	1500
	500	.715	.877	2.66		612	528
	600	.708	.899	2.53		582	330
	700	.699	.889	2.38		548	379
6-A	420	0.710	0.803	2.96	44.9	660	1590
	500	.723	.874	2.80		624	567
	600	.716	.894	2.63		586	366
	700	.703	.886	2.48		552	405
7-20	420	0.677	0.765	2.64	50.5	522	1880
	500	.699	.865	2.49		493	520
	600	.693	.898	2.35		465	316
	700	.681	.878	2.23		441	374
7-35	420	0.697	0.826	2.60	47.9	543	993
	500	.702	.899	2.44		509	289
	600	.693	.912	2.32		484	206
	700	.680	.909	2.18		456	248
7-65	420	0.712	0.827	2.83	44.3	639	1160
	500	.722	.895	2.72		614	378
	600	.715	.908	2.49		585	272
	700	.702	.899	2.44		551	312
7-150	420	0.731	0.815	3.30	45.2	730	1530
	500	.744	.888	3.12		690	587
	600	.737	.901	2.92		646	352
	700	.727	.894	2.79		617	388
7-fines	420	0.433	0.477	1.35	25.3	534	15,300
	500	.498	.620	1.27		502	5840
	600	.508	.669	1.23		486	3980
	700	.502	.677	1.17		462	3560
7-0	420	0.689	0.784	2.99	44.2	677	2720
	500	.713	.849	2.75		622	836
	600	.710	.877	2.60		589	509
	700	.700	.876	2.48		559	491

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS FILM FRACTIONS

Sample	Wavelength nm	n_o	n_{90}	$\frac{n_o + n_{90}}{2}$	$\frac{n_o - n_{90}}{2}$	$s' \times 10^4$	$\epsilon' \times 10^6$
7-A	420	0.691	0.763	2.93	43.5	673	2840
	500	.715	.852	2.76		634	814
	600	.710	.877	2.50		598	517
	700	.700	.873	2.48		570	527
7-B	420	0.613	0.631	3.22	46.3	696	7510
	500	.673	.729	2.96		639	3220
	600	.683	.761	2.77		598	2240
	700	.678	.763	2.69		581	2140
7-C	420	0.648	0.691	2.89	43.7	661	4560
	500	.688	.789	2.66		608	1710
	600	.687	.819	2.48		567	1130
	700	.679	.822	2.35		538	1040
9-20	420	0.577	0.624	2.18	47.8	456	5160
	500	.648	.763	2.21		462	1703
	600	.667	.844	2.16		452	653
	700	.661	.855	2.07		433	532
9-35	420	0.648	0.691	2.89	43.8	660	4560
	500	.707	.803	2.89		660	1994
	600	.722	.866	2.31		641	664
	700	.717	.870	2.72		621	603
9-65	420	0.689	0.710	4.05	45.7	886	5290
	500	.748	.815	3.76		822	1728
	600	.763	.871	3.58		783	748
	700	.757	.869	3.46		757	747
9-150	420	0.710	0.725	4.82	44.2	1090	5680
	500	.771	.825	4.41		998	1852
	600	.787	.874	4.22		955	867
	700	.780	.874	4.00		905	821
9-fines	420	0.595	0.606	3.40	35.4	961	12,300
	500	.672	.689	4.02		1140	7960
	600	.696	.726	3.82		1080	5590
	700	.694	.727	3.70		1050	5360

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS MFL FRACTIONS

Sample	Wavelength mm	n_D	$n_{D\infty}$	$\frac{n_D - n_{D\infty}}{25,400 - \lambda}$	$\frac{n_D - n_{D\infty}}{25,400 - \lambda}$	$\frac{n_D - n_{D\infty}}{25,400 - \lambda}$	$\frac{n_D - n_{D\infty}}{25,400 - \lambda}$
9-0	420	0.679	0.710	3.32	44.9	784	4640
	500	.749	.811	3.86		860	1900
	600	.768	.869	3.72		829	818
	700	.763	.874	3.56		793	721
9-A	420	0.672	0.698	3.63	43.0	849	5550
	500	.739	.803	3.68		836	2070
	600	.757	.854	3.59		835	1040
	700	.750	.854	3.41		792	986
9-B	420	0.675	0.690	4.18	45.4	920	6410
	500	.734	.808	3.49		768	1760
	600	.750	.866	3.33		733	758
	700	.744	.866	3.22		709	734
9-C	420	0.682	0.704	3.92	43.1	910	5660
	500	.748	.814	3.79		880	1870
	600	.763	.869	3.61		838	828
	700	.757	.872	3.43		796	748
9-D	420	0.685	0.697	4.60	40.3	1140	7500
	500	.746	.798	4.00		992	2540
	600	.761	.846	3.75		929	1300
	700	.755	.845	3.62		897	1280
9-E	420	0.618	0.628	3.80	32.2	1180	13,000
	500	.691	.727	2.56		1110	9660
	600	.711	.768	3.38		1090	3680
	700	.705	.768	3.21		996	3490
10-20	420	0.580	0.668	1.86	45.2	412	3400
	500	.621	.801	1.79		396	979
	600	.622	.852	1.72		380	490
	700	.611	.842	1.65		365	540
10-35	420	0.602	0.676	2.10	45.5	462	3580
	500	.644	.804	2.02		444	1060
	600	.645	.853	1.92		422	536
	700	.633	.839	1.84		404	627

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength nm	n_D	n_{∞}	$\frac{n_D - n_{\infty}}{25 \times 10^{-4} - 500}$	$\frac{n_D - n_{\infty}}{25 \times 10^{-4} - 500}$	$S' \times 10^4$	$K' \times 10^6$
10-65	420	0.618	0.686	2.28	46.4	492	9540
	500	.664	.805	2.24		482	1140
	600	.664	.852	2.11		454	573
	700	.658	.846	2.06		443	620
10-150	420	0.645	0.679	3.07	57.1	537	4080
	500	.707	.793	2.98		521	1410
	600	.715	.837	2.83		495	787
	700	.708	.835	2.73		478	780
10-fines	420	0.218	0.299	0.40	27.5	145	11,900
	500	.240	.378	.40		145	7420
	600	.241	.425	.38		138	5360
	700	.235	.433	.37		134	4970
10-0	420	0.586	0.663	1.96	46.1	485	3640
	500	.631	.781	1.93		418	1280
	600	.634	.836	1.85		401	646
	700	.629	.847	1.79		388	536
10-A	420	0.576	0.653	1.89	46.6	406	5740
	500	.615	.770	1.82		391	1390
	600	.618	.822	1.73		371	716
	700	.609	.814	1.68		361	770
10-B	420	0.587	0.670	1.93	44.0	499	9570
	500	.633	.797	1.93		439	1140
	600	.631	.847	1.80		409	965
	700	.624	.840	1.76		400	608
11-20	420	0.530	0.572	1.91	46.6	410	6060
	500	.602	.710	1.90		408	2420
	600	.621	.798	1.81		388	992
	700	.616	.816	1.73		371	772
11-35	420	0.542	0.580	2.04	44.5	498	6970
	500	.608	.715	1.94		436	2480
	600	.626	.801	1.84		413	1020
	700	.623	.815	1.79		402	844

TABLE XIII - continued

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength nm	R_0	R_{∞}	$\frac{5X}{25,400}$	$\frac{W}{-500}$	$\frac{S' \times 10^4}{-500}$	$K' \times 10^6$
11-65	420	0.557	0.584	2.36	45.0	525	7780
	500	.624	.717	2.15		478	2670
	600	.642	.802	1.99		442	1080
	700	.640	.819	1.94		431	862
11-150	420	0.599	0.590	2.30	46.2	498	7100
	500	.633	.719	2.26		489	2690
	600	.658	.796	2.20		476	1230
	700	.657	.812	2.12		459	1000
11-fines	420	0.243	0.297	0.53	33.8	157	13,100
	500	.284	.393	.53		157	7330
	600	.299	.457	.525		155	3000
	700	.298	.477	.51		151	4330
11-0	420	0.527	0.572	1.86	44.6	417	6690
	500	.593	.706	1.83		410	2510
	600	.610	.800	1.71		384	960
	700	.608	.838	1.64		368	578
11-1	420	0.528	0.565	1.97	45.5	433	7260
	500	.598	.702	1.89		416	2640
	600	.618	.798	1.78		391	1000
	700	.616	.816	1.73		380	790
11-3	420	0.526	0.571	1.84	44.6	413	6160
	500	.598	.708	1.87		420	2530
	600	.616	.797	1.76		395	1020
	700	.612	.814	1.69		380	810
12-20	420	0.410	0.437	1.38	37.7	366	13,300
	500	.543	.629	1.64		436	4790
	600	.582	.729	1.63		432	2180
	700	.585	.764	1.58		419	1530
12-35	420	0.450	0.456	2.30	42.5	541	17,600
	500	.606	.660	2.33		548	4800
	600	.649	.763	2.22		522	1920
	700	.654	.797	2.14		504	1310

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength nm	E_{420}	E_{480}	$\frac{E_{420}}{E_{480}}$	$\frac{M}{29 \times 40 - 500}$	$S \times 10^4$	$K \times 10^6$
12-65	420	0.466	0.470	2.40	40.2	596	17,900
	500	.625	.668	2.66		661	5450
	600	.674	.771	2.55		634	2160
	700	.680	.803	2.45		610	1470
12-150	420	0.480	0.481	---	40.2	---	---
	500	.643	.671	3.20		796	6420
	600	.700	.768	3.08		766	2680
	700	.707	.797	2.95		733	1900
12-fines	420	0.508	0.508	---	43.3	---	---
	500	.664	.664	---		---	---
	600	.731	.739	6.20		1430	6590
	700	.747	.758	5.95		1370	5290
12-0	420	0.510	0.515	3.00	37.5	800	18,200
	500	.673	.695	3.42		1080	6820
	600	.730	.768	3.64		971	2770
	700	.744	.826	3.53		942	1720
12-A	420	0.500	0.503	3.20	39.2	816	20,200
	500	.656	.673	3.80		970	7700
	600	.710	.758	3.54		903	3490
	700	.720	.782	3.42		872	2650
Spruce sulfite*	420	0.701	0.801	2.80	46.8	599	1480
	500	.708	.865	2.61		558	586
	600	.700	.880	2.45		523	428
	700	.695	.873	2.40		513	474
Lightly bleached kraft*	420	0.528	0.564	2.00	48.0	417	7060
	500	.607	.705	1.98		402	2480
	600	.630	.796	1.89		394	1030
	700	.629	.826	1.82		380	696
Alpha pulp	420	0.672	0.797	2.37	54.4	436	1130
	500	.675	.865	2.19		403	423
	600	.668	.885	2.08		383	286
	700	.663	.886	2.04		375	275

* These samples were prepared at the same time as were the mixtures of these pulps. It is seen that the results for the spruce sulfite and lightly bleached kraft pulps vary slightly from the results obtained before for these same pulps (Samples 6-0 and 11-0 respectively)

TABLE XIII - Continued

OPTICAL CONSTANTS OF VARIOUS PULP FRACTIONS

Sample	Wavelength nm	R_0	R_{∞}	$\frac{R_0}{R_{\infty}}$	$\frac{R_0}{R_{\infty}}$ 25x40 - 500	$S^2 \times 10^4$	$K^2 \times 10^6$
Mixture A	420	0.611	0.671	2.30	44.3	520	4200
	500	.652	.779	2.12		479	1210
	600	.650	.842	2.07		468	693
	700	.653	.849	2.01		459	610
Mixture B	420	0.679	0.808	2.42	46.2	524	1200
	500	.652	.870	2.26		489	475
	600	.672	.887	2.12		459	330
	700	.661	.880	2.02		437	358
Mixture C	420	0.578	0.584	3.65	36.8	992	24,700
	500	.678	.730	3.07		835	4170
	600	.696	.781	2.89		775	2380
	700	.695	.796	2.74		745	1940
Mixture C'	420	0.547	0.553	3.20	36.8	870	15,700
	500	.642	.700	2.89		704	4520
	600	.662	.753	2.46		669	2710
	700	.661	.765	2.38		646	2340

Mixture A was a 50-50 mixture of bleached spruce sulfite and the lightly bleached kraft.

Mixture B was a 50-50 mixture of bleached spruce sulfite and alpha pulp.

Mixture C was a 50-50 mixture of bleached spruce sulfite and groundwood. This gave a two-sided sheet. C and C' refer to the same sheet with the reflectance measurements made with the light incident on the top and the wire side of the sheet, respectively.