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The Effect of the Rate of Formation on the Structure and Properties of Paper

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THE EFFECT OF THE RATE OF FORMATION ON THE STRUCTURE AND PROPERTIES OF PAPER

by

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ABSTRACT

Paper contains an uneven distribution of fiber fractions through its cross section. The objective of this study was to determine how the rate of formation affected the structure and properties of paper. The structure of paper was analyzed with reference to the cross-sectional distribution of fines and the fines to long fibers ratio in the paper.

The formation rate and distribution of fines were varied by applying a vacuum to the British sheetmold system. As the fines were a different color than the long fibers, their distribution was determined by analyzing the brightness values of layers split from the paper.

The fines used in this study had a substantial effect on paper properties when added to a relatively unbeaten chemical pulp. In general, these additions increased the breaking length, burst, density, and fold and decreased the tear and air permeability of paper. An increase in the rate of formation was found to decrease the ratio of fines to long fibers, although the over-all retention of fibers was increased. Also, the distribution of fines through the thickness of the paper became more disproportionate as the formation rate was increased. Through these two effects, an increase in the rate of formation was found to decrease many strength properties of paper.

TABLE OF CONTENTS

HISTORICAL BACKGROUND

THE FORMATION PROCESS AND THE STRUCTURE OF PAPER

The structure of a sheet of paper can be defined by the spatial distribution and orientation of the various fiber fractions, both across the sheet and through its thickness. Previous investigations have established that the distribution of the various sheet components through the thickness of paper is non-uniform. The first studies were primarily concerned with the distribution of loading material and groundwood with respect to their effect on the two-sidedness of paper. Groen (1), and Underhay (2), using a technique of stripping the paper into layers with adhesive tape, and Lehtinen (3), using a microtome-sectioning technique, found more filler on the felt side than on the wire side of publication grade papers. Judt (4), and Wood (5), and Forgacs and Atack (6) also found a high concentration of groundwood on the felt side of newsprint.

More recently, Treiber, Stenius and Rehnstrom (7), after adding dyed fines to a chemical pulp furnish, found a high proportion of fines on the felt side of the sheet. Brecht and Hoberg (8), substantiated this finding using a similar technique.

Parker and Mih (9) used a Beloit sheet-splitter to split larger sections of paper for cross-sectional study. They used the specific filtration resistance technique to determine the content of fines in the layers stripped from the paper. The specific filtration resistance of any given layer was determined by dispersing the layer in a

known volume of water and placing the suspension in a calibrated column with a fine wire screen at the bottom. The time required for the suspension to pass between two given points on the column was called the specific filtering resistance of the layer. As may be seen in Figure 1, they found more fines on the felt side than on the wire side in fourdrinier made papers.

There has been a great deal of literature published on the causes of the non-uniform distribution of fines in paper. It is generally agreed that during the forming process, the ability of the particles to be entrained by the draining water and to move through the mat is governed largely by the size of the particles relative to the available spaces through which flow can occur. (6) As water is progressively removed from the furnish, the wire acts as a sieve and the long fibers are preferentially retained. The deposited web then acts as a sieve of decreasing mesh size, allowing particles of ever-decreasing size to pass through it. Eventually, the whole mat becomes so compacted that very little further relative movement is possible. Consequently, the composition of the fibrous material and filler at any plane through the thickness of the sheet may vary considerably. (6)

Wrist (10) described the formation process as a self-filtering process in which the three phases (water/fiber/filler) are separated into two solid phases and one liquid phase. At any water removal rate, this process will result in an uneven distribution of materials. In the first stage of drainage the filter mat is formed only by the wire which contains coarse openings compared to the particle size of

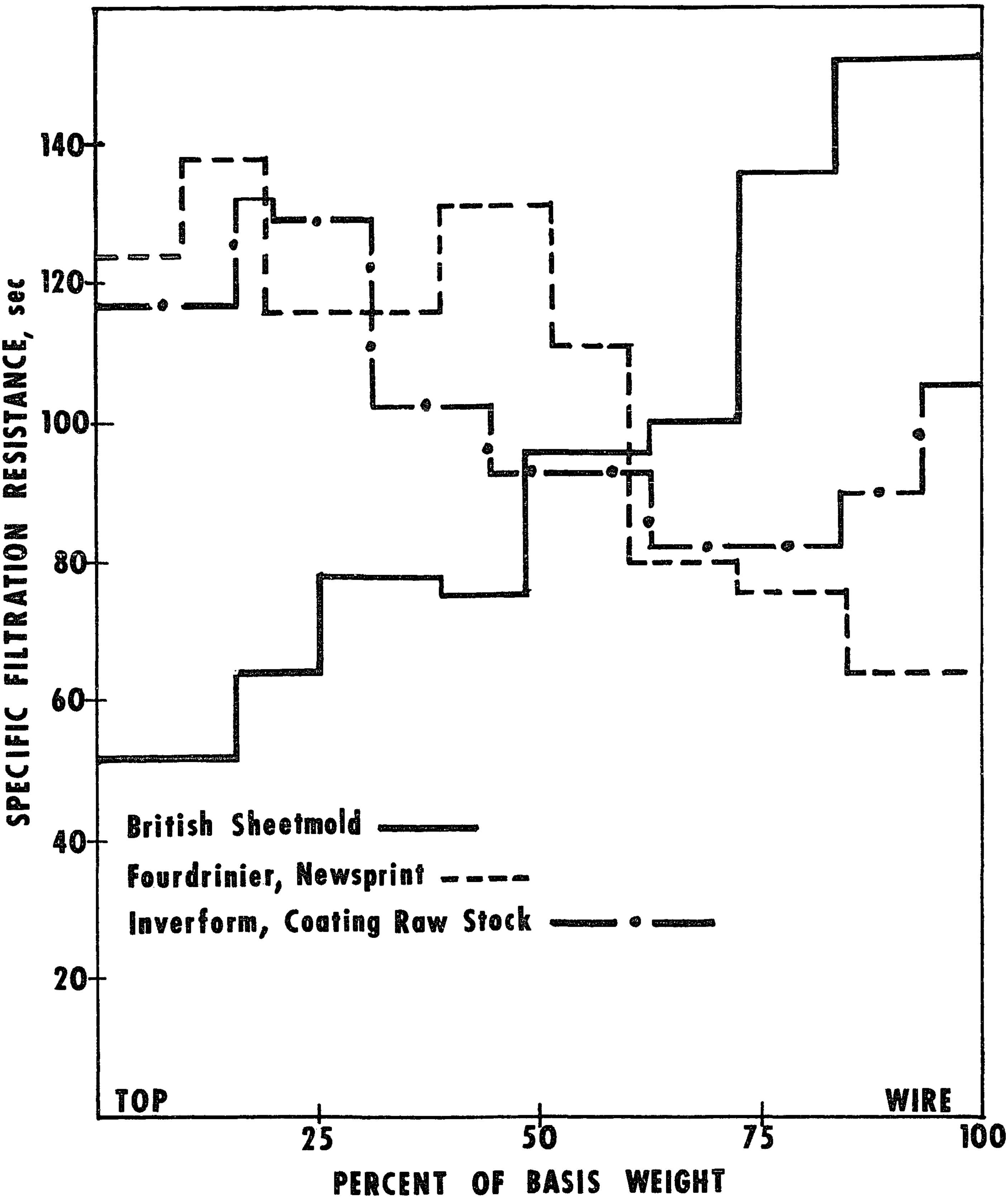

FIG. 1. THE DISTRIBUTION OF FINES IN PAPER MADE BY BRITISH SHEETMOLD, FOURDRINIER, AND INVERFORM (9)

the solid phases. Consequently, the first hypothetical layer will be relatively deficient in fines. The next layer contains more fines because an open layer of fibers now takes the place of the wire as the filter medium. During continued drainage, subsequent layers will be built up, steadily increasing in the content of fines. The fines themselves act as a filter aid by plugging up the pores in the sheet matrix. The top layer will contain fewer fines, however, as the fines will filter down to the next layer. (11)

Hansen (12) and Mack (13) have substantiated Wrist's theory by studying samples of paper taken directly after the breast roll following a sudden shutdown. They both found an uneven distribution of filler already present and concluded that this distribution was caused by the self-filtering of the filler from the system unaided by table roll or foil action.

Another popular explanation of the phenomenon of the uneven distribution of fines is the backwash action of the table rolls. Underhay (2) using simulated drainage conditions on a British sheetmold found that the water advancing under the wire adhered to the table rolls and was wedged into the nip between the rolls and the wire. This water was pushed through the underside of the wire, disturbing the wire side by loosening and resuspending the fines and pigments present. These were then washed from the wire layers decreasing the content of fines and filler on the wire side.

Although explanations for the cause of the uneven distribution of fines may vary, all investigators agree that the concentration of the fines decreases towards the wire side of paper. Groen (1)

studied the effects of filler content, machine speed and dandy roll on the distribution of filler in paper. He found that the distribution was independent of filler content and machine speed while the dandy roll produced a higher concentration of filler on the felt side.

Luhde (15), in studying the effect of wire speed and dandy roll on sheet formation and wire mark, found that increased machine speeds extract more fines and filler from the sheet, the wire side again suffering the majority of the losses.

The work of Hansen (12) and Mack (13) indicated that the table rolls and suction boxes only affected the filler in the immediate wire side surface while the selective filtration process accounted for the uneven distribution of the filler and fines through the rest of the thickness of the sheet.

THE RATE OF FORMATION AND THE DISTRIBUTION OF FINES

Although much work has been done with systems simulating conditions in the formation process, very little has been done to effectively determine the influence of formation rate on the distribution of fines.

Investigators studying related systems generally agree that increased flow rates of air and water can detach small particles from large surfaces. This would happen when the fluid drag force exceeds that of the forces attaching the particle to the surface. However, it is believed that fines are not attached to fiber surfaces but are entrapped by the forming web matrix during the formation process. The distance the fines travel downward during increased formation rates is a function of their size relative to the pore sizes in the

forming web. This movement is further complicated by hydraulic forces, colloidal forces, and system geometry.

Hansen (14) found that an increase in machine speed, which results in an increased drainage rate, decreased the filler content of the paper. Also, an increase in basis weight, at any machine speed, increased the filler content.

Luhde (15) investigated the influence of machine speed and dandy roll on the formation and structure of paper using the following variables as his experimental parameters: 1) the combined vacuum totals of the dry flat boxes, 2) the solids extraction rate at the dry flat boxes, 3) the formation quality of the paper, and 4) the freeness, thickness, and ash content of the felt, felt-middle, wire-middle and wire layers of the paper.

As shown in Figure 2, increases in machine speed from 1200 to 1800 f.p.m. decreased the thickness of the felt and felt-middle layers and the total filler and fines content of the paper. However, the ash content and drainage resistance of the different layers were found to depend only on their position within the sheet, with the wire layers having a higher freeness than the felt layers. Although the use of a dandy roll seemed to improve the formation of paper, especially at lower speeds (See Figure 3), it also resulted in a higher solids extraction rate. This was attributed to the densifying action of the dandy roll whereby the air flow rate through the fiber mat was reduced leading to a higher vacuum level in the flat boxes (See Table I). With the higher vacuum, the velocity of the air and water through the remaining interstices of the compacted web was increased and resulted in greater fines and fillers losses at the vacuum boxes.

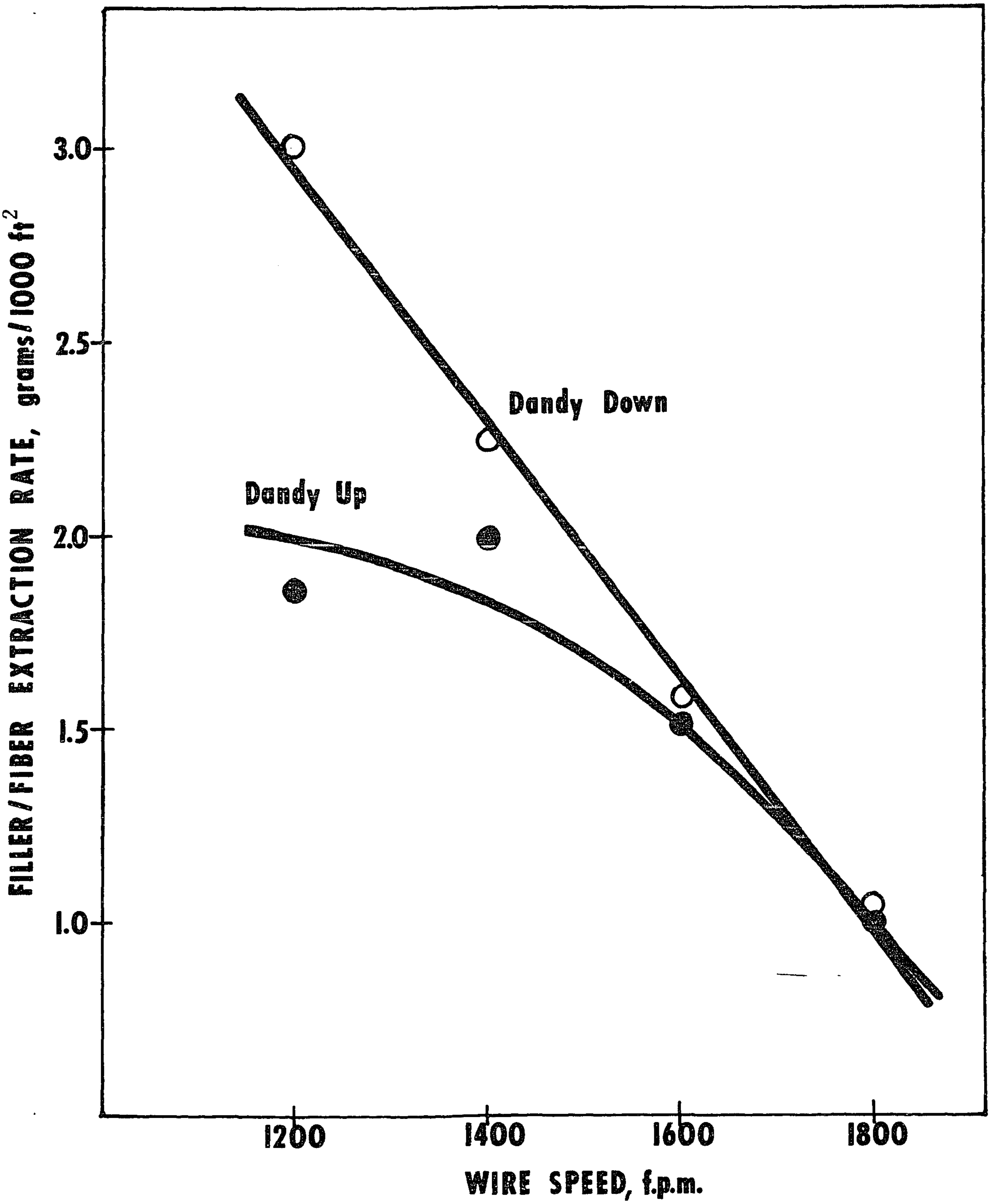

FIG. 2 THE EFFECT OF WIRE SPEED AND DANDY ACTION ON THE FILLER/FIBER EXTRACTION RATE (15)

TABLE I THE EFFECT OF DANDY POSITION AND WIRE SPEED ON THE EXTRACTION CAPACITY OF THE FLAT DRY BOXES (15)

	Dandy Position	Wire Speed in f.p.m. 1200	1400	1600	1800
Total vacuum*, in. water	Down	31.6	32.3	30.3	28.8
	Up	28.1	28.1	25.2	26.4
Extraction Rates, grams per 1000 ft^2 of formed paper of 28 lb. per ream					
Fillers	Down	2.06	2.94	2.89	3.24
	Up	1.31	2.03	2.05	2.52
Fibers	Down	0.86	1.29	1.78	2.55
	Up	0.71	1.07	1.36	1.98

*Sum of the vacuum levels of all 5 boxes

Beer (16), investigating the effects of drainage rate on the retention of titanium dioxide using the British sheetmold, found higher flow rates reduced the over-all retention of titanium dioxide. This was explained in terms of the drag exerted on the titanium dioxide, both from an electrostatic and frictional viewpoint. Beer felt that if the energy keeping the titanium particles in place was less than the energy supplied by increased flow rates, the particles would be sheared loose and redeposited again somewhere lower in the fiber matrix. Therefore, if the energy supplied by the flow rate was great enough, large quantities of titanium could be washed from the system. This was accentuated if large volumes of water were also used.

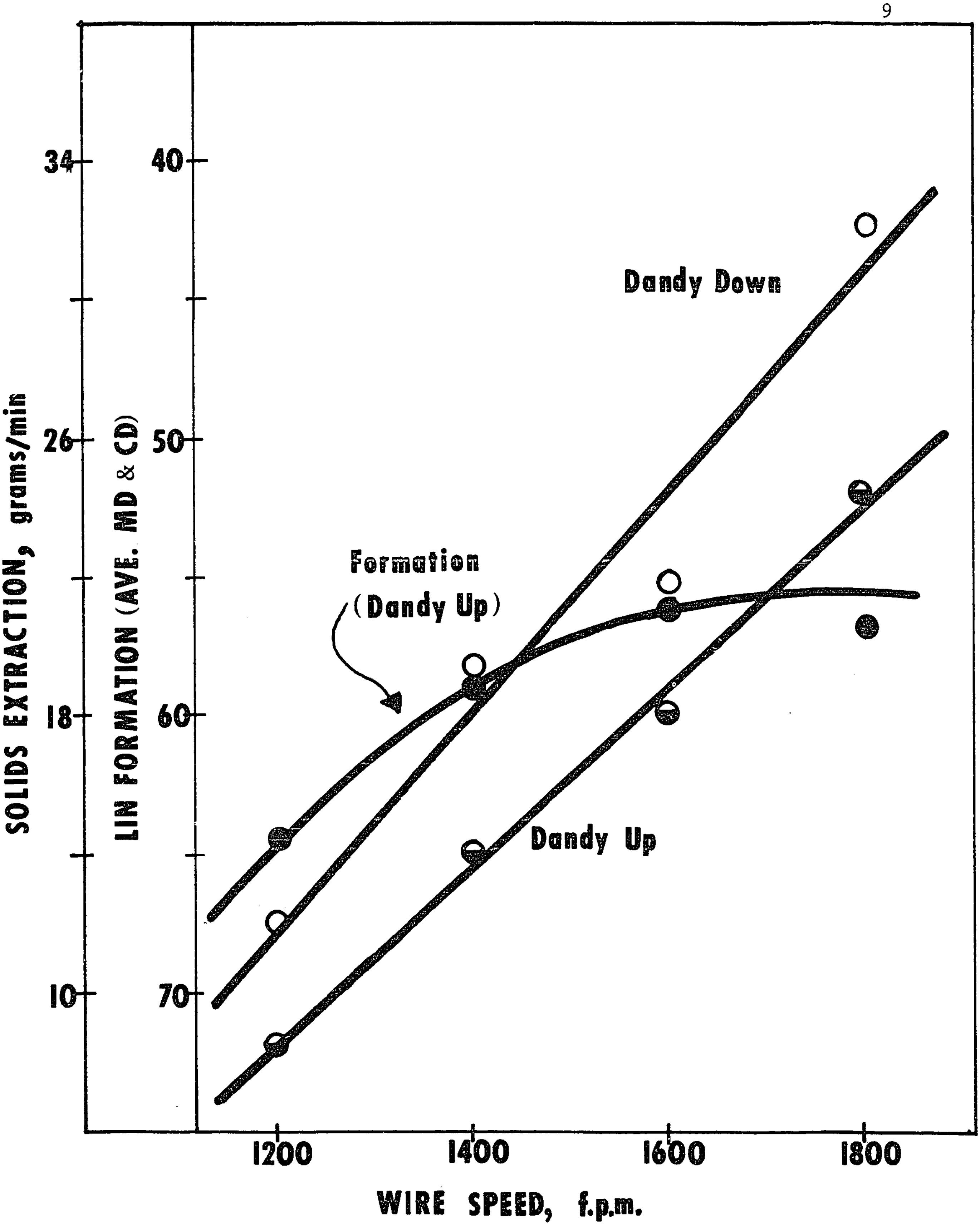

FIG. 3 THE EFFECT OF WIRE SPEED ON THE SOLIDS EXTRACTION RATE AND ON PAPER FORMATION (15)

To summarize the investigations in this area, it can be concluded that increased drainage rates decrease the fines and filler content of paper. Paper made by the fourdrinier process manifests an uneven distribution of fines and fillers, with the top layers containing as much as three times the filler and twice the fines content of the wire layers. Paper made on the British sheetmold exhibits the opposite characteristics with the wire layers containing the higher concentration of fines. Although the use of a dandy roll can help to equalize two-sided filler retention the effect is offset by the densifying action of the dandy roll. The denser sheet creates greater vacuums in the flat boxes which reduces the over-all retention of fines and fillers.

THE EFFECT OF RATE OF WEB FORMATION OF PAPER PROPERTIES

Although there has been some work done on the influence of formation rate on paper structure, very little has been published on the effect of formation rate on paper properties. Norman (17) has studied the effect of wire mesh, drainage rate, consistency and pulp type on British sheetmold paper, the results of which can be found in Table II. The drainage rate was varied by the attachment of vacuum pumps to the drain of the sheetmold.

Norman felt the results could be explained in terms of the fiber length and fiber compressibility. The long, flexible softwood kraft fibers more readily bridged the openings in the wire mesh and quickly established a fibrous filter bed on the wire. In addition, the flexible nature of the kraft fibers imparted a high

TABLE II THE DEPENDENCE OF SHEET PROPERTIES ON FORMING VARIABLES (17)[a]

	Softwood Kraft			Hardwood Kraft			Softwood Semichem. Pulp		
	Drainage Rate, sec			Drainage Rate, sec			Drainage Rate, sec		
	4.1	I[b]	2.4	6.8	I	5.3	3.9	I	1.9
Burst Factor:	81	85	80	52	52	46	59	66	65
Breaking Length:	10.9	10.6	10.8	8.4	8.3	7.0	9.8	9.7	10.3
Tear Factor:	132	138	136	94	102	100	81	79	81
Bulk:	1.59	1.65	1.61	1.52	1.54	1.56	1.60	1.60	1.61
Air Resistance, sec:	30	30	40	133	109	62	27	27	26
Stretch, %:	2.9	2.9	2.9	3.3	3.5	2.9	2.0	1.9	2.1

[a]All sheets were made at a 0.017 percent consistency, using a 44 x 60 mesh fourdrinier wire. The freenesses of these pulps were 450, 100, and 450 CSF, respectively.

[b]I = Intermediate drainage rate. Numerical values were not given.

compressibility to the forming mat. A high drainage rate compressed and densified the forming mat, which allowed a greater retention of the shorter fiber fractions. This mechanism may account for the lower drainage rates of softwood kraft compared to semichemical pulps under fast drainage conditions. The high drainage rate had no significant effect on the physical properties of the paper made from the long-fibered kraft. However, there was significant strength loss in the semichemical pulp because of the greater fiber rigidity and simultaneous loss of shorter fiber fractions. The loss of strength was most pronounced in the hardwood kraft which lacked the long fiber needed to quickly establish a fiber mat on the wire, resulting in an excessive loss of fines and concomitant loss in burst, breaking length, stretch and air resistance.

In summary, Norman felt the nature of the pulp determined the effect that the drainage rate had on sheet properties. Strength losses were explained in terms of the loss of fines and short fiber fractions. If the pulp had fiber length and flexibility, these losses were minimized, even at high drainage rates.

THE EFFECT OF THE CONTENT OF FINES ON THE PROPERTIES OF PAPER

It has long been a matter of conjecture as to whether the fines in paper contribute to its strength development. Ingmanson and Thode (18) have stated, "In the case of an unclassified pulp (made into handsheets) where large amounts of fines were known to be present, the fines have apparently bonded to the surface of parent fibers with the result that the dry fiber surface area remains

essentially constant." Ingmanson and Thode concluded that for a given total bonded area, the strength of paper was independent of the surface area of the fibers or the concentration of fines present. In addition they commented, "The only major role of surface development and fines in producing strength is to provide greater surface tension (The Campbell effect) to draw fibers into close enough proximity for bonds to be established........ It appears that fines are not as effective as an equivalent surface area of fibrils."

Giertz (19) reported that the only visual effect of the content of fines was their drastic effect on the drainage of the pulp. He found that the formation of fines during beating played an important role in determining the porosity of paper but, other than that, seemed to be a side-effect of little value for the improvement of the other properties of paper. Therefore, he felt that the formation of fines should be kept to a minimum.

Somewhat conversely, other investigators have found the fines to control a given property of the whole (unfractionated) pulp. Arlov (20) found that the removal of the fines from sulfite pulps refined by a P.F.I. mill, basalt lava beater and Valley beater reduced the breaking length of the paper made from all three pulps. Other investigators (21 - 23) have found that the addition of fines to pulps increased the breaking length.

Maron and Alexander (24) reported that the manner in which the wood was pulped played an important role in determining the influence of fines on paper properties. By making handsheets from fractionated,

unbeaten, kraft, sulfite, NSSC and stone groundwood pulp, they found the fines of the high yield pulps contributed very significantly to the development of breaking length and burst while adversely effecting the tear. The strength development was attributed to the rather stiff, unhydrated nature of the longer fibers in high yield pulps and to the large quantity of fines present in these pulps (30% in NSSC and 40% in stone groundwood compared to 10-12% fines in full chemical pulps). The fines had minor positive effects on the breaking length and burst strength of kraft and sulfite pulps, but decreased their tear strengths significantly.

Richardson (25) studied the effect of "ultra fines" on the paper strength properties and drainage rate of a NSSC pulp. The fines were considered that fraction of the pulp which passed through a 200 mesh screen. Richardson further fractionated the fines into other sizes which consisted of fines larger than 100 microns, smaller than 100 but greater than 85 microns, smaller than 85 but greater than 60 microns, smaller than 60 but greater than 20 microns and smaller than 20 microns. He then studied the effect of these "ultra fines" on paper properties and found that the burst and tensile strengths continued to increase with the addition of these fines. Furthermore, the strength increases were found to become more apparent as the size of the fines decreased. He added that the strength improvement was possibly sufficient to warrant acceptance of the simultaneous drainage rate decrease, with the exception of the fines smaller than 20 microns. It was therefore concluded that these minute but discrete particles could contribute substantially to an increase in interfiber bonding.

The disagreements evolving from these various investigations could stem from several sources. First, the results are usually based on the initial content of fines of a pulp which may or may not be indicative of the final concentration of fines in the paper. Richardson circumvented this problem by adding fines until a 5% increase in sheet weight was obtained. Also, the results would depend to a great extent on the type of fines being used. If the fines are produced by a refining process, they may or may not have a highly developed surface. If fines have a low surface development they would probably add little to the development of strength in paper. The fines may also originate from the wood as ray cells, vessel segments, or parenchyma cells. Steenberg (22) and Roschier (26) have found differences in the chemical and physical properties of natural fines and those produced by refining. The natural fines had a higher lignin content and added less to the development of strength in paper (27).

The consensus of opinion seems to indicate that, while fines can add to the strength of paper, their adverse effect on drainage may offset any benefit.

PRESENTATION OF PROBLEM

The preceding sections indicate that the fourdrinier process produces paper with an uneven distribution of fines and is relatively independent of any attempts to change this distribution. The problem is that the nature of the fourdrinier process makes it impossible to produce a sheet with a uniform distribution of fines thereby making it also impossible to determine the effect of an uneven distribution on the properties of paper. If it is assumed that fines do add strength to paper, their uneven distribution both laterally and through the sheet may contribute significantly to the "data scatter" so common to paper tests. These small-scale substance nonuniformities introduce localized weaknesses in paper which ultimately cause a reduction in its strength properties.

The present state of the paper industry indicates that the substance nonuniformity common to the fourdrinier process may be reduced by changing to new manufacturing processes, two of which have been introduced in recent years. Common to both is the removal of water from both sides of the sheet, whereby an attempt is made to reduce two-sidedness and the uneven distribution of fines and fillers. It is still too early to evaluate the results of these processes.

The primary objective of this investigation was to determine the effect of the drainage rate on the distribution and ultimate content of fines through the cross section of paper. In turn, these latter phenomena were to be analyzed with respect to their influence on the properties of paper.

EXPERIMENTAL PROCEDURES

THE PREPARATION OF THE LONG FIBER

A bleached softwood kraft (Celgar) was used for the long fiber fraction. The pulp was refined in a 1½ pound Valley beater with a 5400 gram load for 15 minutes at a consistency of 1.56%. The resultant pulp had a freeness of 565 ml, Canadian Standard. A direct dye* was immediately charged to the beater, totaling 6.0% by weight on the oven dry fiber. Twenty grams of salt were then added to set the dye. The temperature of the pulp after the addition of the dye solution was 95°F. The pulp was again dispersed for four hours and soaked for an additional 18 hours after which it was placed in a Bauer-McNett classifier for washing. By running hot water (142°F) through the classifier for four hours the fines and the excess dye were both removed during the same operation. The pulp collected from the 28-, 65-, and 100- mesh screens was used as the long-fibered fraction and will be designated as "Pulp A" throughout the rest of this paper. The average fiber length of Pulp A was determined using microscopic techniques.

Another portion of the same pulp was refined in a 1½ pound Valley beater with a 5400 gram load for 20 minutes at a consistency of 1.25%. The pulp had a freeness of 596 ml, C.S., and was not dyed. The fines were removed in the same manner as before, and

*Calco's Pheno Black SGN Conc. Dustless Direct Dye

the average fiber length of the pulp was again determined. This pulp will be referred to as "Pulp B".

THE PREPARATION OF FINES

One hundred and twenty pounds of bleached softwood kraft (Celgar) was charged to a 240 pound Hollander beater and dispersed at a consistency of 2.0%. The pulp was then refined wtih a Ol-Claflin refiner for two hours to a C.S.f. of 127 ml. The stock was then run on the 30 inch-wide pilot paper machine of the Paper Technology Department of Western Michigan University at a basis weight of 70 pounds per 25 x 38 -500 ream and a speed of 50 feet per minute. A 60 x 75-mesh machine wire was used. The white water was pumped from the wire pit to two 210 gallon tanks to which a 3½ inch Bauer Centricleaner System was attached to clean the fines. After the fines were cleaned at a consistency of 0.22%, a preservative (Dowicide G) was added and the fines were allowed to settle for three days. The fines were then collected from a spout at the bottom of the tank at a consistency of 0.36% and were stored in a refrigerator at 10°C.

THE ESTABLISHMENT OF THE CALIBRATION CURVE

In order to determine the content of fines in the paper, a calibration curve was established plotting the relationship between the percent of fines present and the resultant brightness of the paper. The fines used in this procedure totalled 0, 10, 20, 40, 50, 60, 80, 90, and 100% of the sheet weight. A Millipore membrane filter appa-

ratus with a cellulose acetate filter membrane of 8 micron pore size was used to insure complete retention of the fines in the pad. A diagram of the apparatus is found in Figure 4. Although the pulp slurry was stirred continuously as the pad was being formed, the fines still tended to migrate toward the filter membrane. The brightness data points used were an average of the top and filter-side values.

After the pads were made, they were pressed with the standard British sheetmold equipment in accordance with TAPPI standard T 205 m-58. The pads were dried by placing them between polyvinyl-chloride annular discs made from pipe couplings. Holes were drilled around the periphery of the discs to insure the flow of air over the pad surfaces. Pulp gaskets and a one kilogram weight were placed between and on top of the pads in order to keep shrinkage to a minimum. The pads were dried in a room with a temperature of $73\pm1^{\circ}F$ and a relative humidity of $50\pm2\%$.

THE PREPARATION OF HANDSHEETS

All handsheets were made with deionized water and in accordance with TAPPI standard T-205 m-48 except for the use of a 60 x 75-mesh wire in place of the conventional 150 x 150-mesh handsheet wire. A modified British sheetmold (see Figure 5) was used to permit variation of the drainage rate. To increase the drainage rate, the valves between the vacuum tank and the water-leg were closed and the pump engaged. When the gauge indicated the desired vacuum, the valve between the pump and the vacuum tank was closed and the pump stopped.

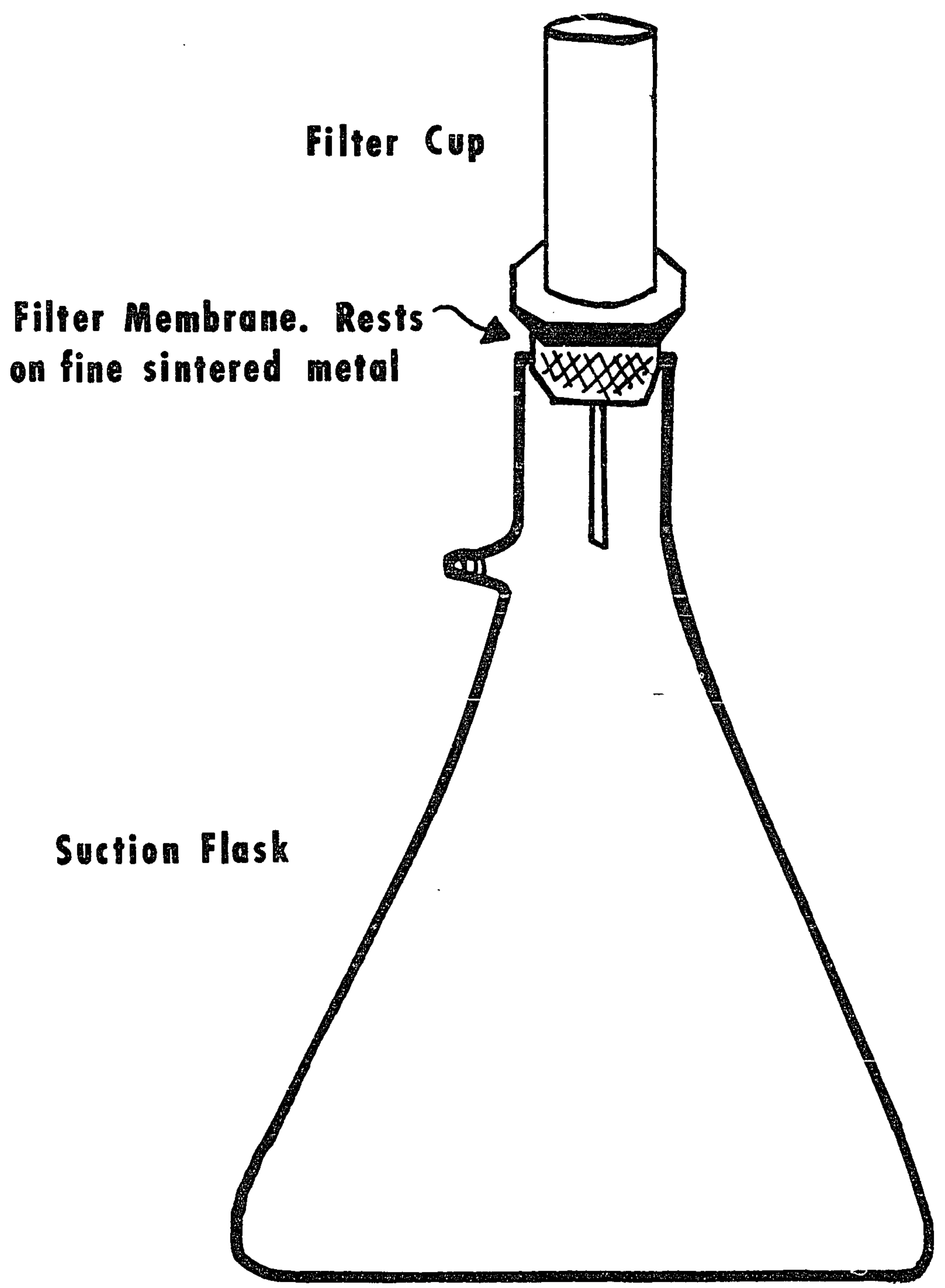

FIG. 4 APPARATUS FOR PREPARATION OF CALIBRATION PAPERS

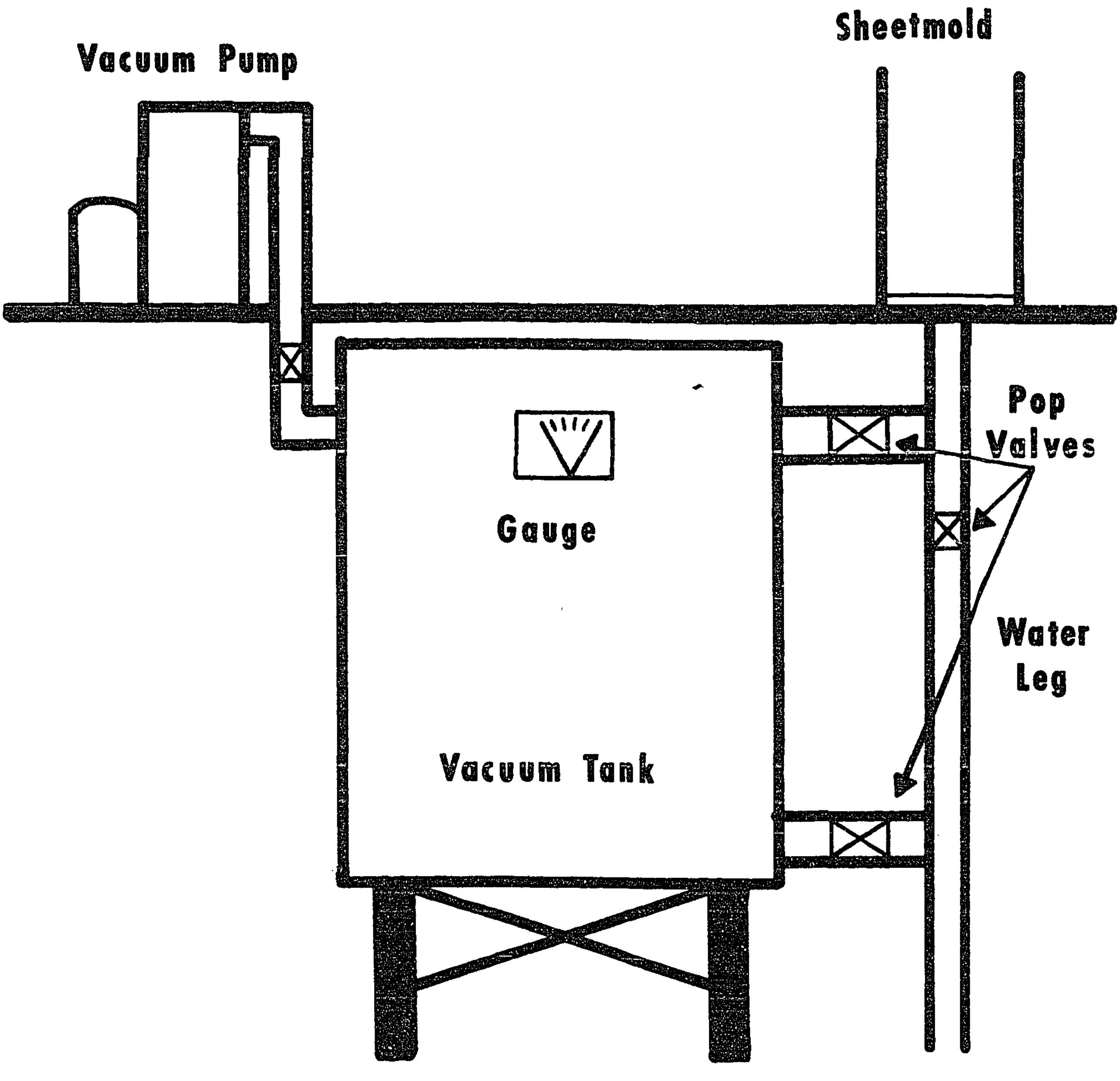

FIG. 5 MODIFIED BRITISH SHEETMOLD

The upper pop valve between the vacuum tank and the water-leg was then opened and sheet formation commenced. The time required for the water level to reach the "dry line" of the sheet was defined as the drainage time. These times were then converted to drainage rates by dividing the values by the distance the pulp slurry traveled (350 mm) in the sheetmold.

Paper was made from Pulp A and contained an initial fines content of 10 and 30%. Each of these sets was made at three different drainage rates.

The paper made from Pulp B contained an initial fines content of 50%. Sets of 15 sheets were made at three different drainage rates. Ten sheets were used to gather the conventional test strength data and five were set aside for the sheet splitting process. The sheets were tested for burst, breaking length, tear, opacity, density, brightness, porosity, tensile energy absorption and elongation. The tests were carried out and the results were calculated in accordance with TAPPI standard T 220 m-60.

THE SHEET SPLITTING PROCESS

The paper made from Pulp B and 50% fines was split into layers with a Beloit sheet splitter (9) to determine the effect of drainage rate on the distribution of fines through the thickness of the paper. Five sheets from each of three sets of paper were split into four layers: top, top-middle, wire-middle and wire. Before the sheets were split, they were trimmed to fit the sheet splitter rolls and soaked for an hour in water. An attempt was made to split the sheets

into four equivalent sections, all layers approximating 25% of the sheet weight. Roll temperature, speed and pressure were used to control the splitting in order to obtain the desired layer weight. After the sheets were split, the layers were slurried and made into pads using the Millipore filter apparatus. The filter membrane had an average pore size of 8 microns insuring complete retention of the fines in the layers. The pads were dried in the same manner as those in the calibration procedure. The amount of fines in the layers was determined using the brightness values of the pads and the calibration curve for Pulp B (See Figure 6).

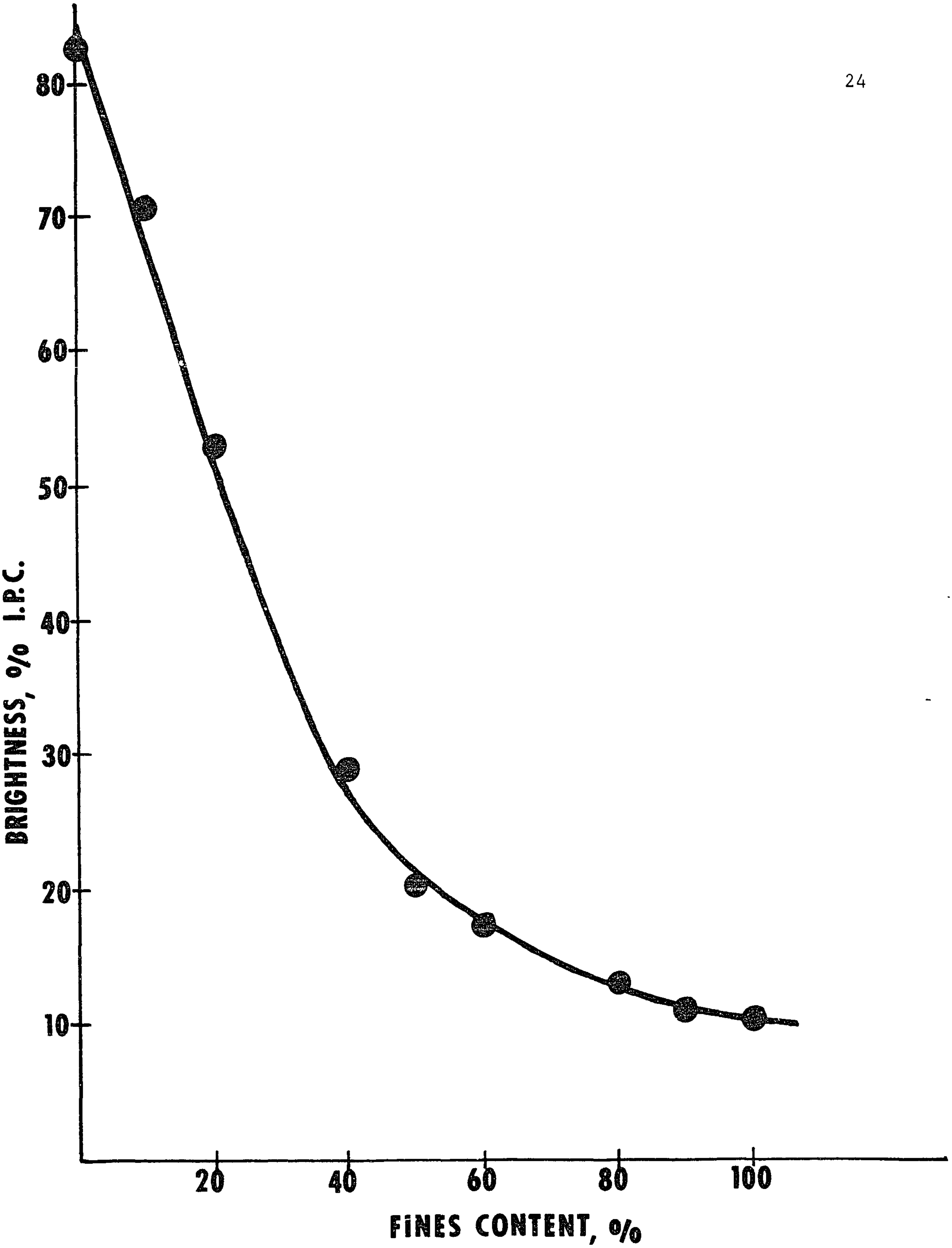

FIG. 6 THE EFFECT OF THE CONCENTRATION OF FINES ON THE BRIGHTNESS OF PAPER MADE FROM PULP B. USED AS CALIBRATION CURVE.

PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

CHARACTERIZATION OF PULP A AND PULP B

It was thought at the outset of this investigation that the brightness of paper made from fines added to a dyed pulp would give a good indication of the final content of fines in the paper. By splitting the sheets into four layers, the brightness values of these layers could also be used to determine the distribution of fines through the thickness of the paper. However, the fines absorbed enough color ions from the water to make their brightness almost that of the dyed pulp, especially in paper containing a low percentage of fines.

Because of the extremely low brightness of the fines, it was felt that the use of an undyed, bleached kraft refined in deionized water would produce the brightness spread needed for this study. Therefore, another batch of pulp, Pulp B, was refined in deionized water. This yielded a pulp with a brightness of 83.4%. Since strength comparisons were to be made between the two pulps, they were refined to approximately the same freeness, Pulp A (dyed) 565 C.S.f. and Pulp B, 596 C.S.f. The average fiber length data, as determined by microscopic analysis, and photographs of both pulps can be found in Appendixes I and II. The photographs show the relatively small amount of refining the dyed and undyed pulps received. The weighted average length of Pulp A was greater than that of Pulp B. This was probably due to the long washing operation

used to remove the excess dye from the fiber. In the process more of the shorter fiber fractions would also be removed.

It is believed that dyeing a pulp with a direct dye after the beating cycle has very little effect on its potential papermaking properties. Centola and Borruso (28) studied the influence of certain substantive dyes (including direct dyes) on the strength properties of softwood sulfite and kraft pulps. They found that the addition of direct dyes to these pulps after the beating cycle was completed had no effect on the strength properties of the paper. Therefore, the difference between Pulp A and Pulp B was assumed to be negligible.

THE CONSTRUCTION OF THE CALIBRATION CURVE

The calibration curve was established by adding known percentages of fines to Pulp B and forming sheets on the Millipore filter apparatus. The brightness values of the pads were determined for each level of fines addition and were plotted against the percentage of fines added. These results can be found in Table III and Figure 6.

CHARACTERIZATION OF FINES

Microscopic measurements and photographs were used to characterize the fines. As can be seen in the photographs of Appendix III, the fines have been completely disintegrated to fibril bundles. Their highly developed surface is also very apparent. The largest dimension of the fines was determined to be 0.2 to 0.3 mm.

TABLE III SUMMARY OF CALIBRATION CURVE DATA OBTAINED USING FINES, PULP B AND MILLIPORE FILTER APPARATUS

Fines Content,%	Brightness,% I.P.C.	Basis Weight, g/m^{2}*
0	83.4	202.6
10	70.5	198.3
20	53.1	204.4
40	28.7	192.4
50	20.4	191.5
60	17.7	193.5
80	13.0	193.4
90	11.6	206.1
100	10.1	204.5

*The discs were trimmed with a punch to a diameter of 1.92 cm. before weighing.

THE EFFECT OF THE CONTENT OF FINES ON PAPER PROPERTIES

Inspection of Table IV and Figures 7 and 8 indicates that many of the strength properties of paper made from a slightly beaten softwood kraft can be substantially increased by the addition of fines to the pulp. Increases in the fold, breaking length, burst and density of the paper were produced by the addition of fines while the tear and air permeability were decreased. These results were found to be highly significant when analyzed statistically at the 99 percent confidence level (See Appendix IV). Only those properties that were significantly effected by the addition of fines (at the 99% confidence level) were plotted in Figures 7 and 8.

Fines are highly developed in surface area and therefore have a greater hydrogen bonding potential per unit weight than the long fibers in an unbeaten chemical pulp. The addition of fines to such a pulp should increase the degree of interfiber bonding in the paper. The data indicates that the properties considered to be primarily influenced by interfiber bonding, i.e. burst, breaking length, fold and density, are in fact significantly increased by the addition of fines. The tearing strength continually decreased with increasing fines addition suggesting an inverse relationship between tear and interfiber bonding (the addition of fines).

All of the above relationships seem to generally agree with the accepted response of fibers to beating. A beating time curve for a chemical pulp produces strength results very similar to those obtained here. An increase in the beating time increases the fold,

TABLE IV THE EFFECTS OF THE CONCENTRATION OF FINES ON PAPER PROPERTIES

Vacuum, in Hg:	0			15		
% Fines added:	10	30	50	10	30	50
Basis Weight, g/m^2	78.7	73.6	73.8	70.8	73.8	79.6
Drainage rate, mm/sec	64.8	21.9	1.4	125.0	32.1	2.3
Density, g/cc	0.583	0.643	0.634	0.551	0.592	0.642
Breaking length, m	6428	8143	8763	5424	6838	7856
Elongation, %	3.7	3.7	3.9	3.6	4.4	2.8
Tensile Energy Absorption, joules	0.259	0.342	0.133	0.200	0.303	0.126
Burst factor	50.2	61.2	67.4	46.0	57.8	59.6
Tear factor	237	154	107	250	178	113
Fold, M.I.T.	1016	1362	1922	842	1429	2524
Porosity, Gurley, sec	33	697	>86,400	18.1	361.0	>86,400

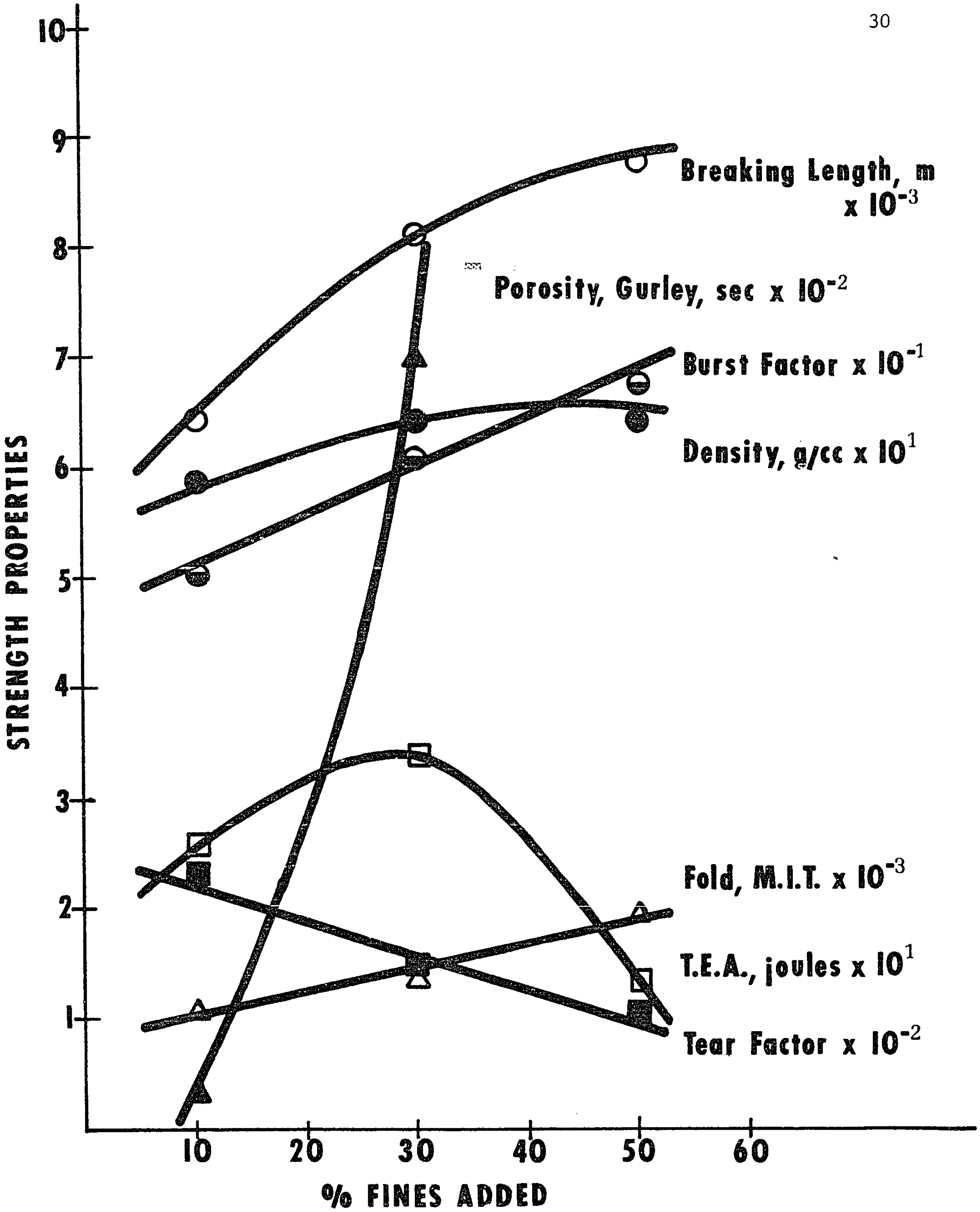

FIG. 7 THE EFFECT OF THE CONCENTRATION OF FINES ON THE PROPERTIES OF PAPER MADE AT ZERO IN. Hg VACUUM

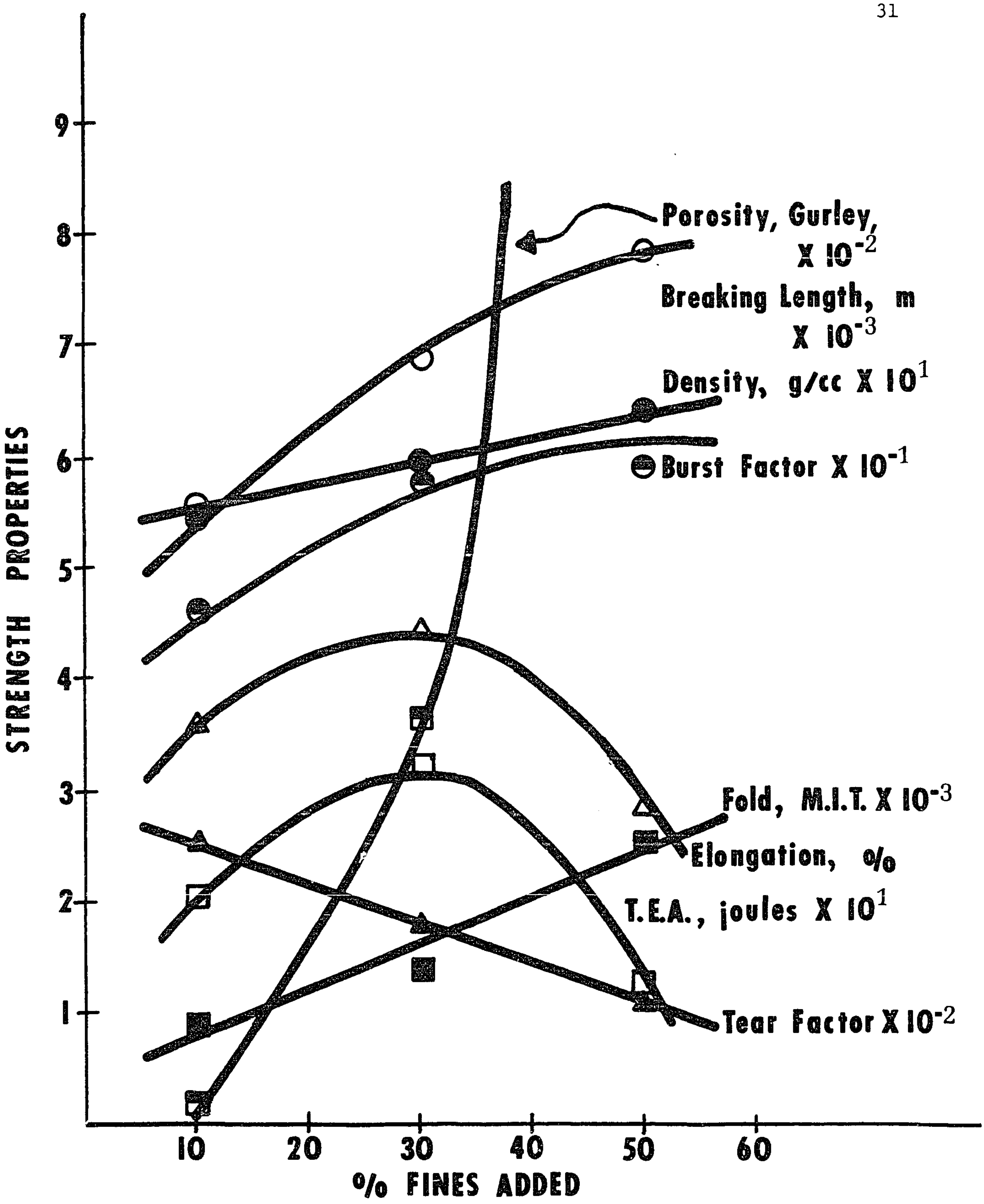

FIG. 8 THE EFFECT OF THE CONCENTRATION OF FINES ON THE PROPERTIES OF PAPER MADE AT 15 IN. Hg VACUUM

burst, density and breaking length and decreases the air permeability and tear of paper.

Although a multitude of factors ultimately determines the degree of development of a given strength test, the influence of the surface area of a pulp is considered one of the most important. That beating increases the surface area of a pulp is a well known phenomenon and it is generally accepted that this increase in surface area, by way of fibrillating the fibers or reducing their size, is primarily responsible for the changes produced in paper strength properties. The results found here suggest that an increase of surface area of a pulp can be obtained by adding fines to a pulp and that this increase may be as effective in producing paper strength as refining. The fact that beating and the addition of fines to an unbeaten chemical pulp similarly influence the interfiber bonding properties of the paper seems to indicate that the degree of surface area development of a pulp is the prime criterion for the production of interfiber bonding rather than the methods used to achieve this development. However, this is not to say that all fines will affect paper in the same manner. The above discussion applies only to the addition of fines to an unbeaten chemical pulp.

The effect of the fines on the drainage rate was quite dramatic. Table IV (p. 29) and Figure 9 indicate that a five-fold increase in the initial content of fines decreased the drainage rate by a factor of 46, under normal drainage conditions. Increasing the vacuum to 15 in. Hg further decreased the drainage rate to a point where a stock with 10% fines drained 55 times faster than a stock with 50% fines.

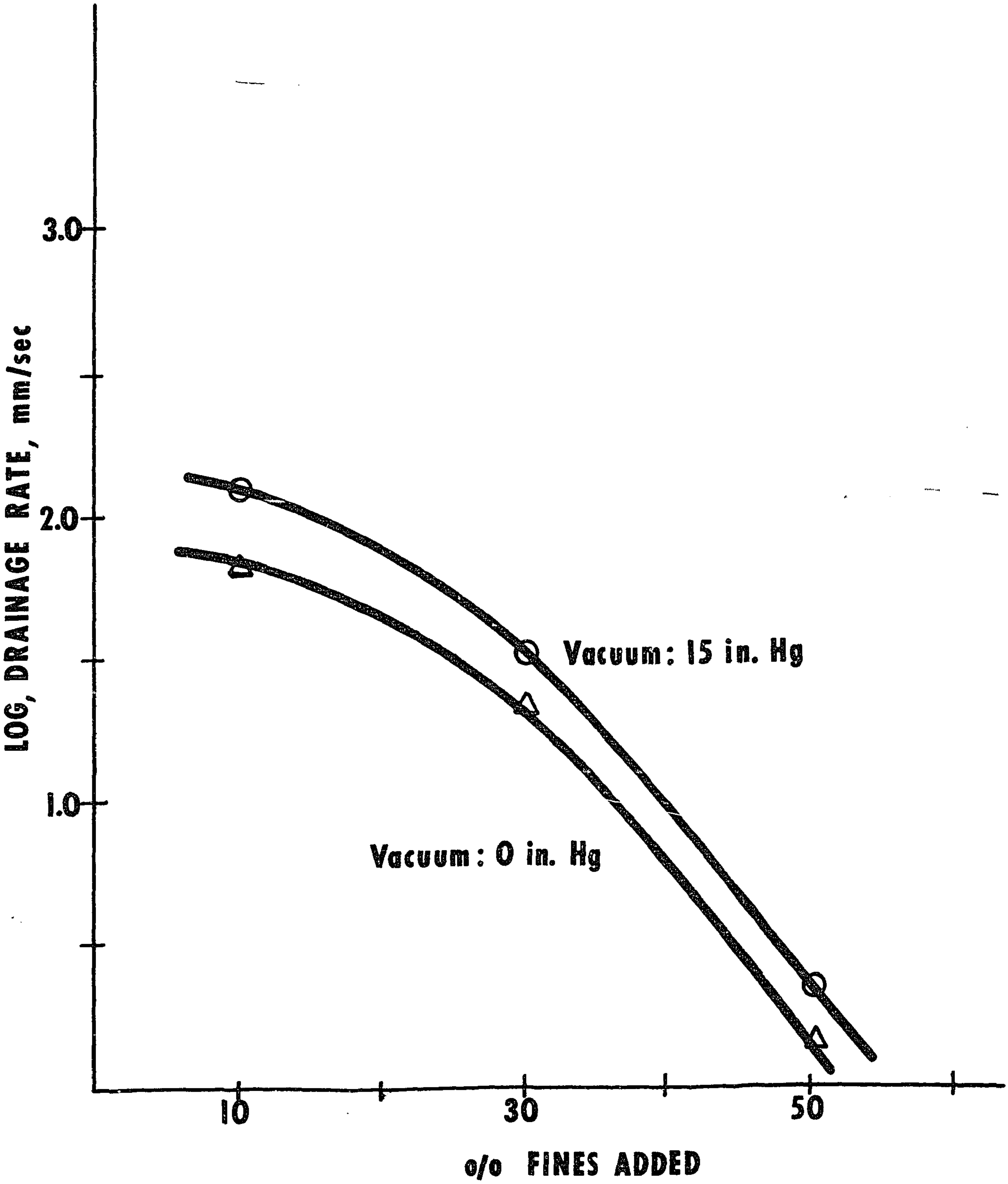

FIG. 9 THE EFFECT OF THE CONCENTRATION OF FINES ON THE DRAINAGE RATE

It is suggested that the fines of a pulp fill in the pores of the forming web during the formation process, decreasing the size of the channels through which the water must flow, causing a decrease in the drainage rate.

Although the drainage rate and its relation to paper properties will be discussed later, the data presented in Table IV and Figures 7 and 8 support conclusions to be drawn later and therefore merit a few comments at this time. It can be seen that an increase in the vacuum from 0 in. to 15 in. Hg definitely reduced the influence the fines had on the strength properties, i.e., the density was decreased by 4%, the breaking length by 14%, the T.E.A. by 14%, the burst factor by 8.6% and the air permeability by 48% (figures based on the average percent decrease for all three concentrations of fines). It is felt the explanations for these results revolve around the effect of the drainage rate on the total concentration of fines in the paper, on the formation of the paper, or on the distribution of the fines through the thickness of the paper. In later sections, the drainage rate will be discussed with reference to these factors.

THE EFFECT OF DRAINAGE RATE ON THE RETENTION OF FINES IN BRITISH SHEETMOLD PAPER

The sheets made from 50% fines and Pulp B were split into four layers in order to determine the effect of the drainage rate on the distribution of the fines through the thickness of the sheets. It was hoped that any redistribution of fines induced by a change in

the drainage rate could account for concomitant changes in the strength properties of the paper.

In order to establish a relationship between the distribution of fines and their influence on paper properties, the total content of fines in the sheets should be the same. This requirement was based on previous results (See Figures 7 and 8) which clearly demonstrated that the concentration of fines can have a substantial effect on a number of strength properties. Table V summarizes the effect of the drainage rate on the retention of the fines in the sheets that were split. Although doubling the drainage rate from 1.4 mm/sec to 2.7 mm/sec increased the over-all retention by 6.4%, the actual retention of fines decreased by 6.0%. It can also be seen that as the drainage rate was increased, the structure of the paper was somewhat altered with regard to the ratio of its fibrous elements. The ratio of the long to short fibers (fines) showed a small but consistent increase as the drainage rate was increased. Also, the over-all retention of fibers increased with increasing drainage rate. This could be explained by considering the interaction of the fibers in the forming zone. When the formation process begins, the descending fibers become entangled in the zone directly above the wire. Those fibers which do not become entangled pass through the network and the wire. As more fibers descend into the zone, a wet web of fibers begins to consolidate allowing fewer and fewer fibers to escape from the system. Eventually, the wet web becomes so compact that it is essentially impervious to all

TABLE V THE EFFECT OF THE DRAINAGE RATE ON THE FIBROUS STRUCTURE OF PAPER

Drainage Rate, mm/sec	Over-all Retention, %	Initial Fines Content, %	Final Fines Content, %	Fines Retention, %	Final Ratio: Fiber/Fines
2.7	74.5	51.0	31.0	60.8	2.23
2.3	74.3	50.5	31.6	62.6	2.16
1.4	70.0	50.2	32.5	64.7	2.08

but the smallest of the fibrous particles. The fines and other small fiber pieces are retained if they become entrapped both between and at the intersection of fibers.

If the rate of water removal in the above system was increased, several changes in the system could occur. First, the fibers would very likely be deposited in the forming zone at a faster rate than in the previous situation, establishing a wet web in a shorter period of time and resulting in the retention of more fiber. Secondly, the velocity of the water passing through the wet web and the wire would be greater. Since the wet web is never completely impervious to the smaller fibrous particles, the velocity of the water could have a pronounced effect on the amount of fines washed from the system. If the force of the water exceeds the energy binding the fines to the fibrous network, the fines could be dislodged and washed from the system.

In such a manner, sufficient increases in the drainage rate could cause selective retention of the longer fiber fractions at the expense of the fines and produce paper that is structurally different than paper made at lower drainage rates. In this experiment, the increase in the drainage rate was great enough to effect only a small but consistent difference in the final content of fines in the sheets. The results suggest, however, that greater losses of fines would be generated by further increases in the drainage rate.

THE EFFECT OF DRAINAGE RATE ON THE DISTRIBUTION OF FINES IN BRITISH SHEETMOLD PAPER

As indicated in Table VI and Figure 10, higher drainage rates generally tended to aggravate two-sidedness in paper having an initial fines content of 50%. The sheets were made under normal drainage conditions (0 in. Hg vacuum) showed a rather uniform distribution of fines, although the top side had a slightly higher concentration of fines than the other three layers. As the drainage rate was increased, the fines were definitely distributed more unevenly throughout the thickness of the sheets. Although this pattern was generally true for the total thickness of the sheets, the effect of the drainage rate on the individual layers was not as apparent. Figure 11 gives a clearer picture as to how the four layers were affected by the drainage rate. The fines in the top two layers (T_1 and T_2) exhibited no definite trend with drainage rate increases although one might interpret the sudden upward shift of the fines to the T_1 layer as a "trapping" effect produced by faster web formation. The effect of the drainage rate on the wire layers (W_1 and W_2) was much more noticeable as the concentration of fines in these layers was substantially decreased with drainage rate increases. The loss of fines was most pronounced in the extreme wire layer (W_1).

The pattern of the fines distribution, as depicted by Figure 10, seems to comply quite well with the discussion of the previous section concerning the effect of the rate of formation on sheet structure.

TABLE VI THE EFFECT OF DRAINAGE RATE ON THE DISTRIBUTION OF FINES IN BRITISH SHEETMOLD PAPER. SUMMARY OF THE SHEET SPLITTING DATA.

Drainage Rate, mm/sec	Weight of Layer, Percent of Total		Brightness, % I.P.C.	Fines Content, %
1.44	T_1	39.2	33.2	36.0
	T_2	18.4	37.8	32.0
	W_2	14.3	34.6	32.7
	W_1	28.1	35.9	33.6
2.27	T_1	41.1	35.5	34.0
	T_2	19.7	35.7	33.9
	W_2	16.2	42.3	29.0
	W_1	22.7	39.6	31.0
2.72	T_1	35.6	32.2	37.0
	T_2	16.8	37.3	32.8
	W_2	21.5	44.3	27.8
	W_1	26.1	46.2	26.4

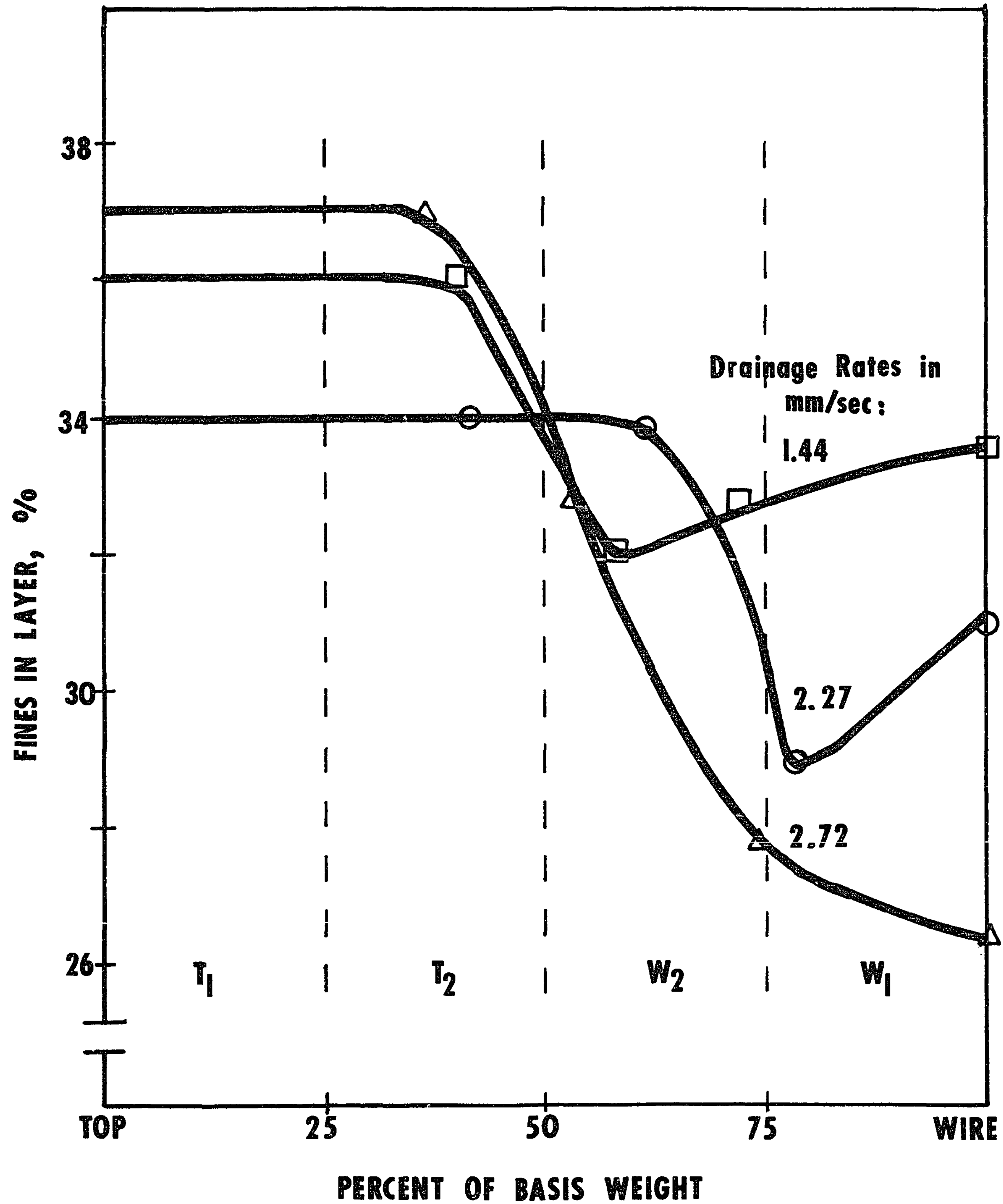

FIG. 10 THE EFFECT OF THE DRAINAGE RATE ON THE DISTRIBUTION OF FINES IN BRITISH SHEETMOLD PAPER

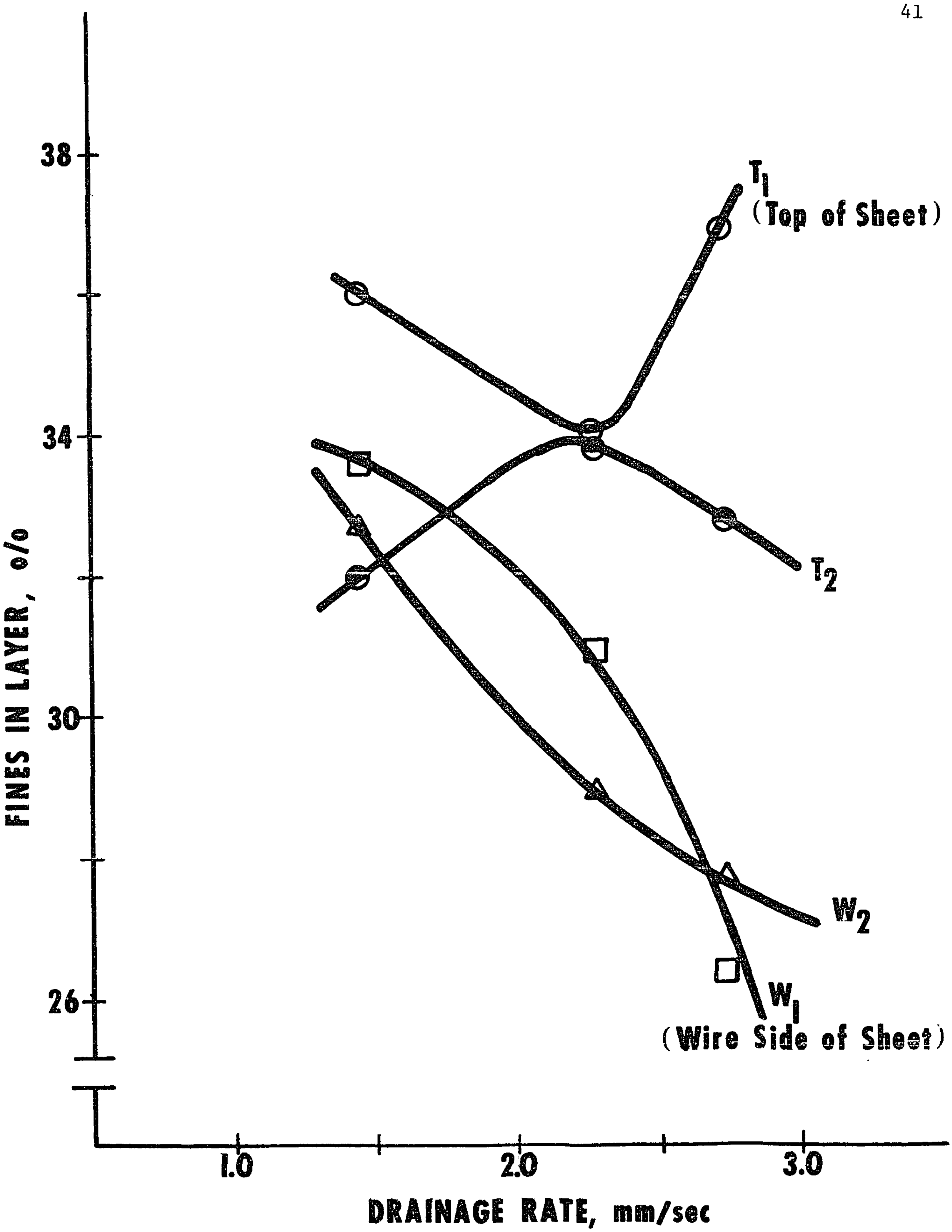

FIG. 11 THE EFFECT OF THE DRAINAGE RATE ON THE CONTENT OF FINES IN THE SEPARATE SHEET LAYERS

As was mentioned then, the time required for the wet web to consolidate depended on the concentration of fibers in the forming zone which in turn depended on the drainage rate. When considering the case of paper made under normal drainage conditions (0 in. Hg vacuum), the following mechanism seems applicable. Fibers descend into the forming zone, become entangled, and a network begins to form. During this time a large proportion of fines and shorter fibers have probably been able to work their way through the porous network and the wire. As time proceeds, the density of the network increases resulting in the retention of more fibers and fines. As the fines are washed from the wire layers, fines from the upper layers sift downward to replace them. Since the wet web is probably never completely impervious to fines, a factor controlling the retention of fines in the wire layers during the later stages of the formation process could be the velocity of the water passing through the web. In this case, however, the energy possessed by the departing water was not great enough to remove the fines from the wire layers. The above process should result in a continual shift of fines downward and out of the sheet. As such, the loss of fines may be great but their distribution through the cross section of the paper should not be unduly disproportionate.

In the case of the high drainage rates, a dense fiber network would form much faster than at low rates, allowing fewer fibers and fines to pass through the web. Because the fibers and fines would be fixed more rigidly into position within the web, there would be less tendency for the fines in the top layers to migrate

downward as was the case in the paper made under slower drainage conditions. However, the velocity of the water could be great enough at high drainage rates to dislodge the fines from the wire layers because of their proximity to the wire. Thus, in contrast to the previous example, paper made under increased rates of formation manifests an uneven distribution of fines.

THE EFFECT OF DRAINAGE RATE ON PAPER PROPERTIES

The influence of the drainage rate on the properties of paper is shown in Table VII and Figure 12. The analysis of variance and standard deviation data for these results can be found in Appendixes V and VI. Figure 12 includes only those properties that were significantly effected by the drainage rate (at the 99% confidence level). In the paper made from 30% fines the breaking length, tensile energy absorption, density and air permeability were substantially decreased by a five to six fold increase in the drainage rate, while the tear was increased. Although Table VII indicates that increased drainage rates produce somewhat the same effects on paper made with a higher concentration of fines (50%), the degree of influence was greatly reduced. The only property that was significantly effected by the drainage rate was the elongation. This phenomenon could be explained by examining the effect of the concentration of fines on the drainage rate. As the sheetmold vacuum was increased from 0 to 25 in. Hg, the drainage rate of the pulp with 30% fines was increased by 470% while the drainage rate of the pulp with 50% fines was increased by only 93%. Also, the

TABLE VII THE EFFECT OF THE DRAINAGE RATE ON PAPER PROPERTIES

% Fines Added:	30			50		
Vacuum, in. Hg:	0	15	25	0	15	25
Drainage rate, mm/sec:	21.9	32.1	125.0	1.4	2.3	2.7
Basis weight, g/m^2	73.6	73.8	68.9	73.8	79.6	76.1
Density, g/cc	0.643	0.592	0.619	0.634	0.642	0.686
Breaking length, m	8143	6838	6762	8763	7856	8001
Elongation, %	4.1	4.4	4.3	3.9	2.8	4.1
Tensile Energy Absorption, joules	0.342	0.303	0.264	0.133	0.126	0.135
Burst factor	61.2	57.8	57.1	67.4	59.6	59.6
Tear factor	154	178	182	107	113	117
Fold, M.I.T.	1362	1429	1257	1922	2524	1951
Porosity, Gurley, sec	697	361	51	all greater than 86,400		

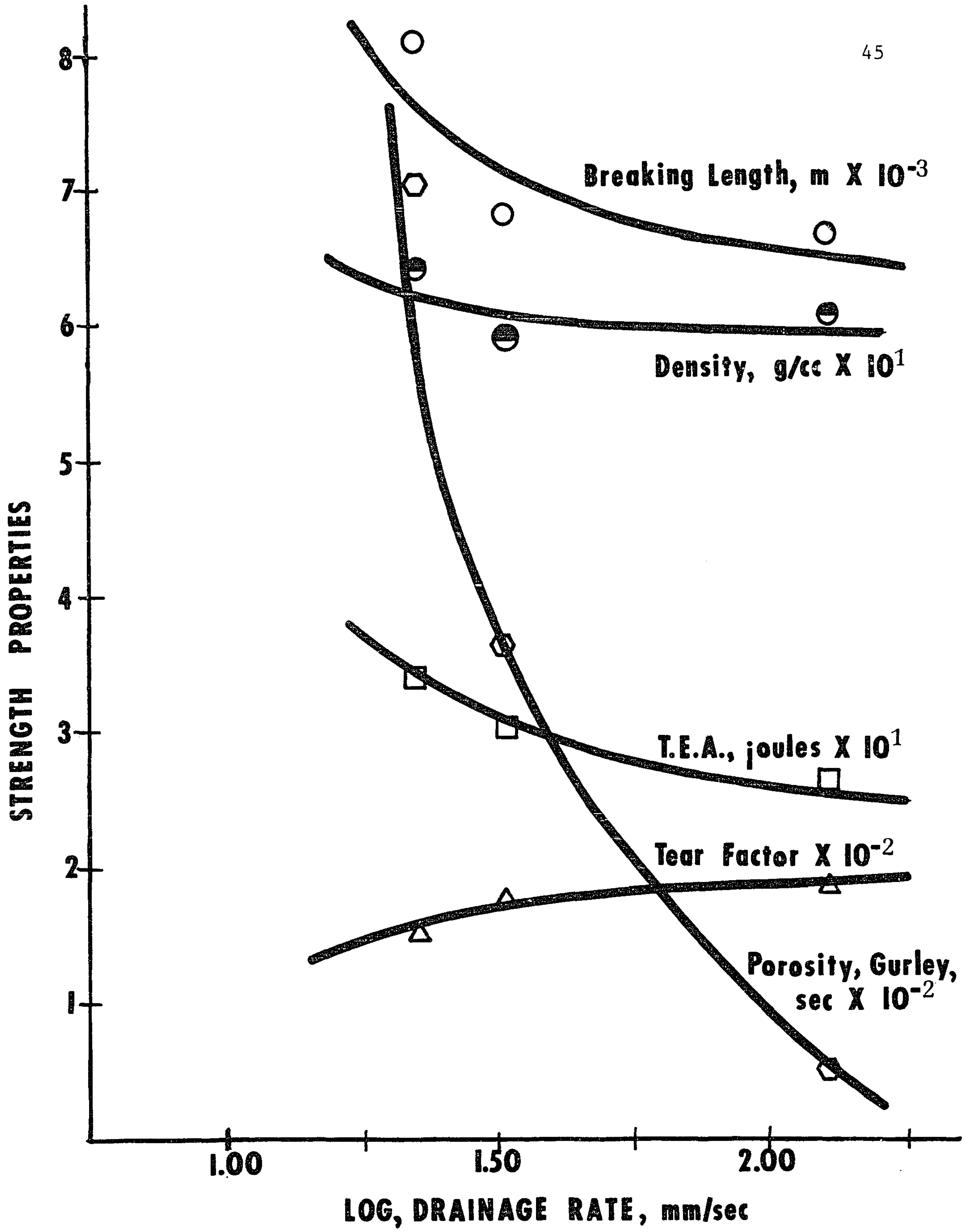

FIG. 12 THE EFFECT OF THE DRAINAGE RATE ON PAPER PROPERTIES (30% FINES ADDED)

pulp containing 30% fines drained approximately 30 times as fast as the pulp with 50% fines (based on the average drainage rate for all vacuums). Evidently the increase in the drainage rate was not great enough to substantially change the properties of paper made from 50% fines. Consequently, it can be said that the effect of the drainage rate on paper properties is primarily controlled by the initial surface area of the pulp.

SUMMARY AND CONCLUSIONS

The fines of a highly beaten softwood kraft pulp made a very major contribution to the development of paper properties when added to an unbeaten softwood kraft pulp. With the exception of the tear, most of the strength properties, i.e. the breaking length, burst, density and fold, were increased by the addition of fines. The air permeability of paper was found to decrease dramatically with the addition of fines and was therefore determined to be the paper property most sensitive to the content of fines. At the same time, however, the drainage rate of the pulp was considerably reduced by an increase in the concentration of fines. Therefore, any real gain in paper strength obtained by the addition of fines to a system would have to be balanced against the simultaneous decrease in the drainage rate.

By applying a vacuum to the British sheetmold system the drainage rate was increased. Relatively small increases in the drainage rate were found to increase the over-all retention of fibers while slightly decreasing the ratio of fines to long fibers. The increased drainage rates also served to relocate the fines through the thickness of the paper to a more uneven distribution, with the fines concentrating in the top layer and being removed from the wire layer.

The properties of paper were significantly affected by changes in the drainage rate if the changes were of a great enough magnitude.

In turn, the magnitude of the drainage rate change was found to depend upon the concentration of fines in the pulp. In a pulp containing 50% fines, the drainage was reduced to such an extent that an applied vacuum had a relatively minor effect on further changing the drainage rate. By decreasing the concentration of fines in the pulp to 30%, a five to six fold increase in the drainage rate was obtained which served to increase the tear of the paper while decreasing the breaking length, density, air permeability and tensile energy absorption. These results were explained by the effect of the drainage rate on the fines/long fiber ratio and the distribution of fines through the cross section of paper.

To summarize, the addition of fines to a chemical pulp produced effects not unlike those produced by beating. Fines contain a large amount of surface area per unit weight and therefore are quite effective in producing interfiber bonds and strength increases in paper. Fines are also most effective in reducing the drainage rate. It may be possible, however, that for a given set of strength test data, the drainage rate may be more adversely effected by beating a pulp than by the addition of fines to the pulp. There was also evidence that fines can contribute more effectively to increases in the strength of paper if they are distributed more uniformly through the thickness of the paper.

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APPENDIX I

SUMMARY OF THE FIBER LENGTH ANALYSIS FOR PULPS A AND B

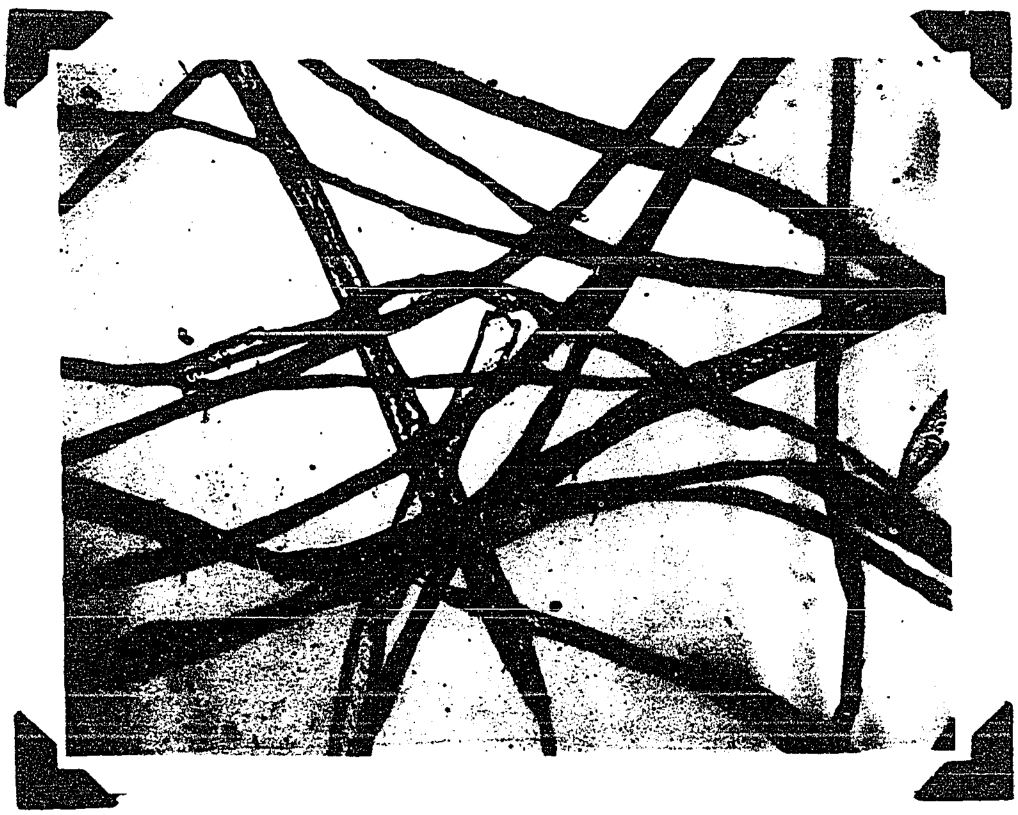
Size, mm	Frequency		No. Ave. Fiber Length, mm		Number, %	
	Pulp A	Pulp B	Pulp A	Pulp B	Pulp A	Pulp B
0.5-1.0	11	33	0.92	0.86	5.5	15.5
1.0-1.5	25	32	1.32	1.28	12.5	15.1
1.5-2.0	33	39	1.76	1.80	16.5	18.4
2.0-2.5	22	29	2.30	2.34	11.0	13.7
2.5-3.0	30	33	2.76	2.81	15.0	15.6
3.0-3.5	32	15	3.30	3.29	16.0	7.1
3.5-4.0	2	19	3.80	3.71	10.5	9.0
4.0-4.5	18	8	4.27	4.31	9.0	3.8
4.5-5.0	3	2	4.70	4.70	1.5	0.9
5.0-5.5	2	2	5.25	5.30	1.0	0.9
5.5-6.0	2	-	5.75	-	1.0	-
6.0-6.5	1	-	6.50	-	0.5	-
	200	212			100.0	100.0

Arithmetic Ave. Fiber Length: Pulp A 2.69 mm
Pulp B 2.24 mm

Weighted Ave. Fiber Length: Pulp A 3.18 mm
Pulp B 2.73 mm

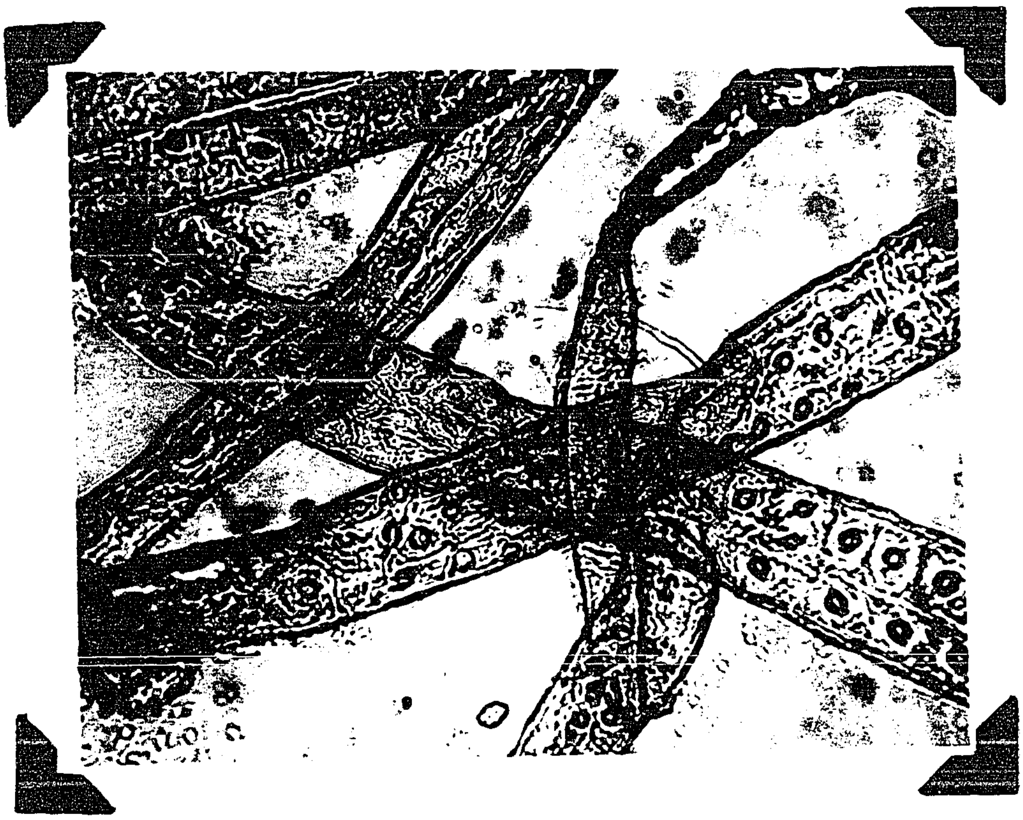
APPENDIX II

PHOTOGRAPHS OF THE LONG FIBERS SHOWING THE UNDEVELOPED NATURE OF THEIR SURFACE



Pulp A (Dyed) Mag. 75X

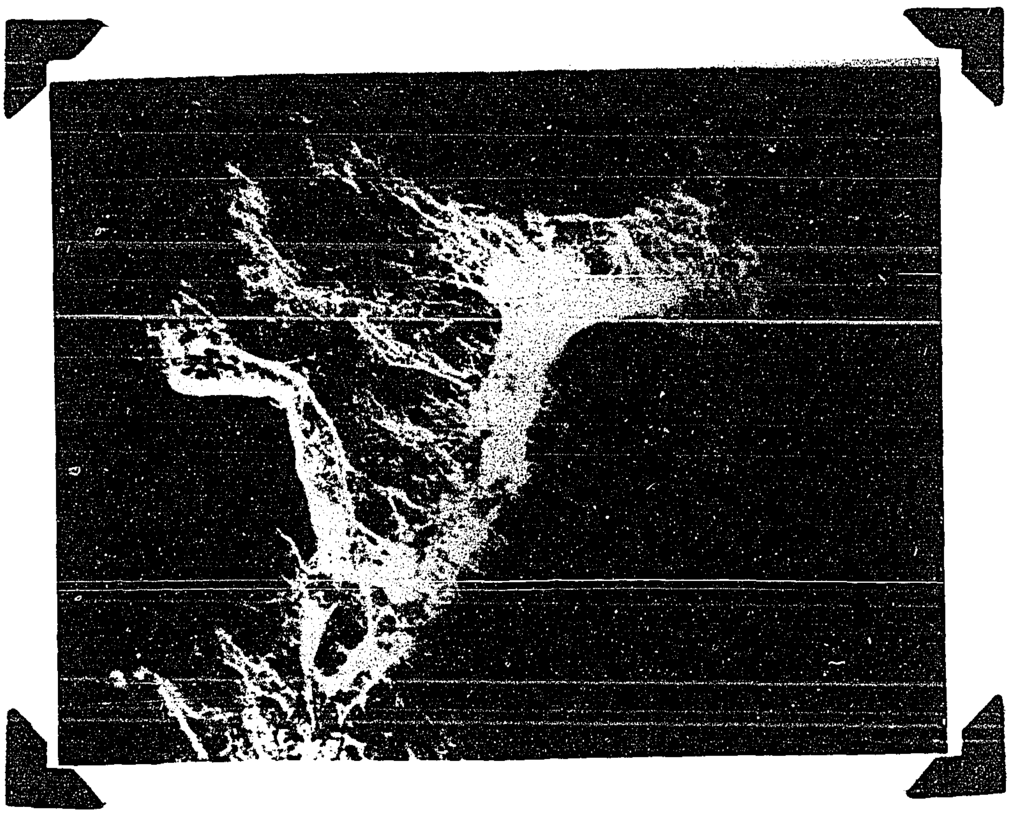
APPENDIX II (cont.)



Pulp B Mag. 300X

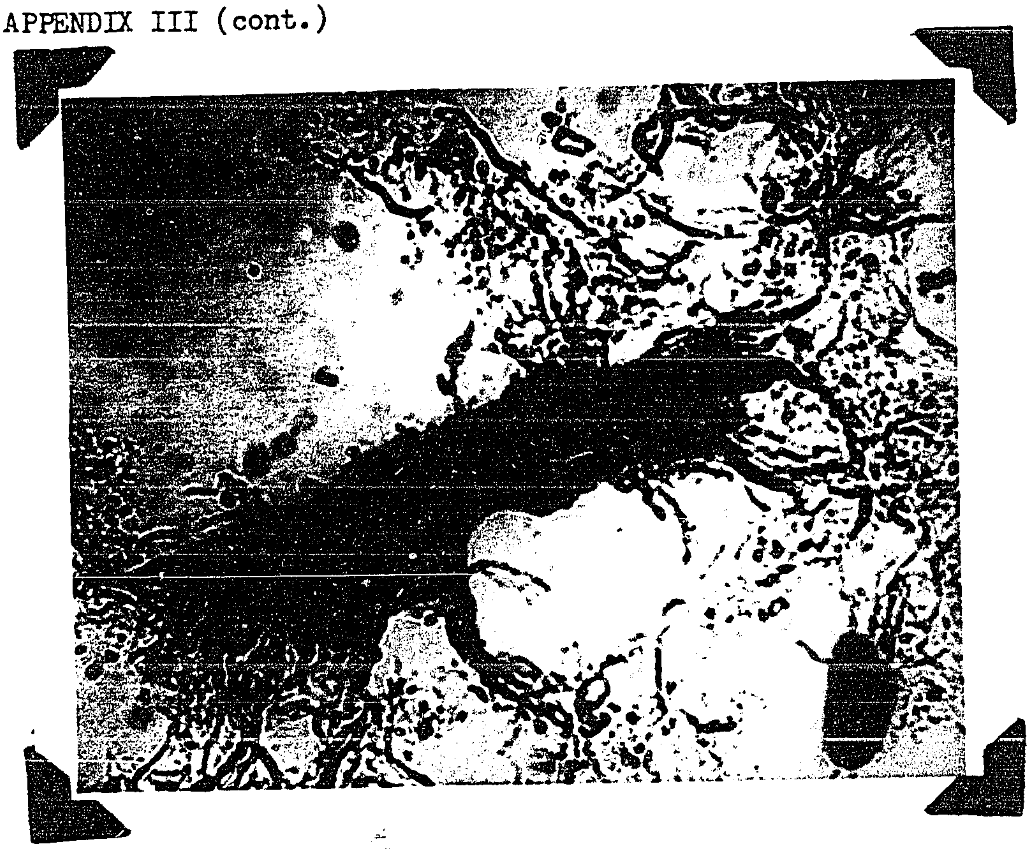
APPENDIX III

PHOTOGRAPHS OF FINES SHOWING THEIR HIGHLY DEVELOPED SURFACE AND LACK OF FIBER STRUCTURE

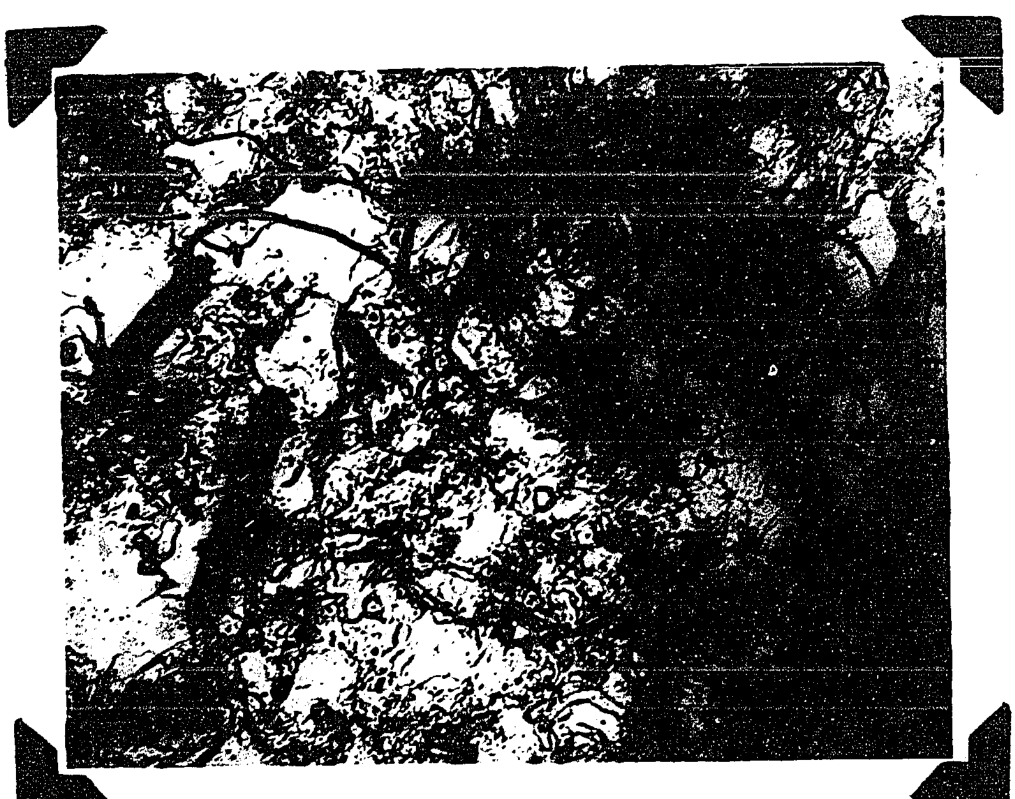


Polarized light Mag. 150X

APPENDIX III (cont.)



Mag. 300X



Mag. 150X

APPENDIX IV

ANALYSIS OF VARIANCE DATA FOR THE EFFECT OF THE PERCENT FINES ON PAPER PROPERTIES

Vacuum, in. Hg:	0		15	
Fines Added, %:	10, 30, 50		10, 30, 50	
	df[a]	F Values	df	F Values
Density, g/cc	2,34	Cal. 13.3 99% 5.30[b]	2,30	Cal. 36.2 99% 5.39
Breaking length, m	2,23	Cal. 38.3 99% 5.66	2,25	Cal. 34.5 99% 5.57
Tear factor	2,24	Cal. 765 99% 5.61	2,23	Cal. 503 99% 5.66
Burst factor	2,50	Cal. 46.8 99% 5.08	2,44	Cal. 24.5 99% 5.15
Fold, M.I.T	2,19	Cal. 24.9 99% 5.93	2,17	Cal. 21.1 99% 6.11
Elongation, %	2,23	Cal. 1.52 99% 5.66	2,21	Cal. 25.5 99% 5.78
Tensile Energy Absorption, joules	2,22	Cal. 54.0 99% 5.72	2,23	Cal. 61.2 99% 5.66

a. Degrees of Freedom
b. F values from standard tables at 99% confidence level

APPENDIX V

ANALYSIS OF VARIANCE DATA FOR THE EFFECT OF THE DRAINAGE RATE ON PAPER PROPERTIES

Fines Added, %:	30		50	
Vacuum, in. Hg:	0, 15, 25		0, 15, 25	
	df[a]	F Values	df	F Values
Density, g/cc	2,30	Cal. 7.20 99% 5.39[b]	2,25	Cal. 5.16 99% 5.57 95% 3.39[c]
Breaking length, m	2,26	Cal. 30.0 99% 5.53	2,23	Cal. 2.31 99% 5.66 95% 3.42
Tear factor	2,22	Cal. 21.5 99% 5.72	2,21	Cal. 5.53 99% 5.78 95% 3.47
Burst factor	2,51	Cal. 3.42 99% 5.07	2,27	Cal. 4.14 99% 5.49 95% 3.35
Fold, M.I.T.	2,22	Cal. 0.75 99% 5.72	2,13	Cal. 2.20 99% 6.70 95% 3.81
Elongation, %	2,25	Cal. 0.90 99% 5.57	2,18	Cal. 13.3 99% 6.01 95% 3.55
Tensile Energy Absorption, joules	2,25	Cal. 5.84 99% 5.57	2,19	Cal. 0.23 99% 5.93 95% 3.52
Porosity, Gurley, sec	2,22	Cal. 78.3 99% 5.72	----	Cal. ---- 99% ---- 95% ----

a. Degrees of freedom
b. F values from standard tables at 99% confidence level
c. F values from standard tables at 95% confidence level

APPENDIX VI

STANDARD DEVIATION DATA FOR THE EFFECT OF THE PERCENT FINES AND DRAINAGE RATE ON PAPER PROPERTIES

Vacuum, in. Hg:	0			15			25	
Fines Added, %:	10	30	50	10	30	50	30	50
Density, g/cc	0.020	0.020	0.051	0.024	0.016	0.028	0.040	0.038
Breaking length, m	444.3	450.1	709.5	211.0	330.8	899.5	470.6	870.1
Tear factor	7.85	6.79	3.78	10.62	8.06	6.72	12.68	7.16
Burst factor	3.57	5.20	6.66	5.11	4.88	8.47	5.18	5.42
Fold, M.I.T.	154.4	252.7	200.3	181.7	251.0	722.9	295.4	348.8
Elongation, %	0.28	0.44	0.62	0.46	0.46	0.29	0.40	0.37
Tensile Energy Absorption, joules	0.028	0.047	0.027	0.180	0.043	0.029	0.047	0.021
Porosity, Gurley, sec	3.00	103.1	---	5.07	115.5	---	12.49	---
Drainage Time, sec	0.14	0.83	19.7	0.02	1.00	9.70	9.12	10.2