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# Characterizing Fines to Predict Their Performance in a Sheet of Paper

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# CHARACTERIZING FINES TO PREDICT THEIR PERFORMANCE IN A SHEET OF PAPER



by

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## ABSTRACT

Many studies have been performed with the purpose of determining the effects of fines on paper properties. However, many of these studies fail to develop characterizations of the fines themselves before relating the presence of these fines to sheet properties. This study first developed complete characterizations of fines and then related the properties of the fines to properties of paper containing these fines.

Bleached kraft, unbleached kraft, and TMP pulps from a southern pine were used in this project. Characterization of the fines included determination of physical features of the fines, size distribution, water retention value (WRV), drainability, and compressibility. Fines were then replaced in their respective pulp sources in levels from 0% to 30%. Handsheets were made and tested to determine various strength and optical properties.

Results showed the bleached fines to be fibrillar, compressible, and hydrophilic. Presence of these fines promoted burst and tensile strength, while tear, opacity, and brightness suffered. Unbleached fines were a mix of flake-like and fibrillar material. These fines also promoted tensile and burst, while tear strength suffered. The TMP fines were comprised of chunky and flake-like material, and exhibited poor water holding and compressibility characteristics. Presence of these fines in a sheet promoted tensile and tear indexes, but decreased the scattering coefficient of the sheet.

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# INTRODUCTION

The role of fines in a sheet of paper and maximizing their potential to improve sheet quality is becoming more important in light of increasing demands on sheet quality and ever-increasing pulp prices. Most studies in this area, however, fail to develop indepth characterization of the fines themselves before evaluating the effects of the presence of the fines in the sheet of paper. Therefore, the purpose of this thesis is to perform detailed characterizations of fines and relate these characteristics to sheet properties.

# THEORETICAL AND BACKGROUND

## EFFECTS OF FINES ON SHEET PROPERTIES

Many studies have been performed to try to determine the effects of fines on sheet properties. The results regarding this seem rather mixed. Comparing results from these studies is complicated by the fact that in each individual case, there were may variables to consider. These include wood species, pulping method, whether or not the pulp has been refined, and the definition of fines size.

In a study of fiber and fines fractions in spruce TMP, Corson (1) found fines material (-200 mesh) to make an important contribution to the consolidation of the sheet. Increasing the fines content in the sheet resulted in increases in wet web tensile index and elongation, dry sheet density, tensile index,

elongation, and scattering coefficient. A decrease in tear value was seen. When the long fibers in the furnish were well refined, Corson found that lower proportions of fines were needed to reach the maximum strength values. At very high levels of fines addition, loss of dry tensile, elongation and tear index were seen. Corson noted that the only justification for adding the extra fines to reach this level of fines in the pulp would be to increase scattering coefficient and air flow resistance of the sheet. This will, however, come at the expense of sheet strength losses.

Mohlin (2) found similar results in a study of fines (-200 mesh) from two different thermomechanical pulps. Increasing levels of fines in the sheets resulted in increased tensile strength, initial wet-web strength, and Scott Bond strength. Tear index showed variable results. Mohlin went on to say that the size of the fines fraction was the dominant factor determining the properties of the sheet and not the properties of the fines themselves. This is a rather questionable statement, in light of the fact that the fines were only characterized by size, leaving questions regarding the properties of the fines themselves that Mohlin referred to. An important point was raised in this study regarding the formation process for handsheets for testing. Mohlin felt that in order to maintain just comparisons of properties between pulps, the white water should be recycled during formation to ensure comparable retention of fines in each sheet.

In a study of PGW, TMP, and SGW pulps of Norway spruce, Lindholm (3) found that the presence of fines (-200 mesh) in increasing levels in a sheet resulted in increases in density, Scott Bond strength, and tensile index. These gains came at the expense of drainability of the pulp. Tear index showed increases at low fines levels, followed by decreases at fines levels exceeding some point in the sheet. These results were true for all three pulp types. Light scattering was highest for the least refined fines, with scattering coefficients decreasing with decreasing freeness levels. Lindholm went on to remark that the light scattering coefficient of isolated fines fractions does not directly predict the performance of these fines in a sheet, as other variables enter into consideration. He calculated an effective light scattering coefficient using the following equation for 25% fines in a sheet:

$$s = 0.75 \times S_{c+m} + 0.25 \times S_{1/f}$$, where:

$s$ = light scattering coeff. of whole pulp

$S_{c+m}$ = light scattering coeff. of sheets of 50% coarse fraction, 50% middle fraction

$S_{1/f}$ = effective light scattering coeff. of fines fraction at 25% fines

Again, it should be noted that the characterization of the fines involved in this study was based on size of the fines alone. Thus, other characteristics of the fines that may have an impact on sheet properties were not considered.

Miller, Peterson, and Shankar (4) studied the effects of fines (-200 mesh) of CTMP of mixed density hardwoods treated with 7% NaOH. From tests of handsheets made from each pulp fraction, they found that sheet density and tensile strength increased as the fibers became finer. The sheets made from whole pulp were found to be the strongest. This clearly indicates that the fines were contributing to sheet strength. Sheets made with no fines were compared to sheets made of whole pulp, again showing higher strength for the sheets with fines present.

Iwamida, Sumi, and Nakano (5) worked to characterize fines and identify their role in developing paper properties for Abies sachalinensis and Betula platyphylla on the basis of their water retention values. Primary fines (-150 mesh) and secondary fines (-200 mesh) were treated individually. They chose neutral sulfite, bisulfite, and acid sulfite pulps for their study. They found that the WRVs for the fines fractions were much greater than for the fiber fractions. Through SEM analysis, they found the secondary fines to be very film-like, adhering well to the fiber surfaces. This was attributed to the high degree of swelling of the fines. This visual quality was in agreement with increasing tensile strength with higher WRV. The secondary fines were found to yield a stronger sheet than the primary fines. The light scattering coefficient of paper made containing fines was also related to the WRV. With the improved bonding that comes with higher WRV for fines, there were fewer fines available

for light scattering, resulting in a drop in this value. It was also seen that a decreasing pulp yield resulted in lower light scattering coefficients. This correlated with the increasing WRV as yield dropped. Primary fines were found to give more light scattering, as they were not as active in bonding as secondary fines.

Richardson (6) studied the effects of NSSC hardwood pulp "ultra-fines" on the strength properties of paper. Fines passing through a 200-mesh Bauer-McNett classifier screen were further fractionated into five classes: fines larger than 100 microns, those between 85 and 100 microns, 60 to 85 microns, 20 to 60 microns, and those smaller than 20 microns. Fines from each of these fractions were then added to the original, unclassified pulp at a ratio of 5% and 95% fines and whole pulp, respectively. Results showed fines of smaller size resulted in a stronger sheet (burst and tensile). At the same time, however, drainage time increased considerably. Richardson felt that the strength improvement may be sufficient to justify the loss in drainability, with the possible exception of the fines fraction smaller than 20 microns.

Giertz (7) found that removing the fines from refined bleached spruce sulfite and bleached birch sulfate pulps resulted in lower sheet densities than seen with whole pulp sheets. The higher density for whole pulp sheets tended to correspond to better bonding in the sheet. This was also in agreement with

higher tensile stiffness, tensile strength, and rupture elongation seen in the whole-pulp sheets. Light scattering was found to be lower, also in agreement with the improved bonding. Giertz attributed the increased bonding to stronger Campbell's forces. He found fibrillated fibrils and fines to contain extra-large amounts of bound water in the swollen hemicelluloses at their surface. Values of bound water were determined by centrifugation and solute exclusion. In a wet web, these fibril/water and fines/water groups will form strong wet bonding between fibers. During drying, this system will shrink as a glutinous gel, pulling the fibers together, thus forming the fiber-fiber bonds in the dry sheet. Increased amounts of fines will enhance this process, thus resulting in a stronger sheet.

Hawes and Doshi (8) found that when unbleached kraft or recycled pulp fines (-200 mesh), whether primary or secondary, were added to an unrefined recycled kraft pulp, significant increases in sheet density, tensile strength, burst strength, tear index, and fold resulted. These fines were found to have no significant effect on the scattering coefficient of the sheet of paper. Since the scattering coefficient can give some indication of the degree of bonding in the sheet, it is clear that these fines are engaged in bonding, making them unavailable for light scattering. When TMP fines were used, scattering coefficients went up dramatically. This was in agreement with the fact that the TMP fines did not improve sheet strength. The addition of

fines to the recycled pulp led to decreases in the air permeability of the sheet. In analyzing the compressibility of the fines, it was found that the secondary recycled and kraft fines were much more compressible than TMP fines. As these fines were more compressible, there was a greater opportunity for intimate fiber contact, thus improving bonding, as was seen in the strength tests. Through chemical analysis, it was found that the secondary fines of the TMP had a higher hemicellulose level than the primary fines, while the hemicellulose level for chemical pulp fines was higher for the primary fines. In regard to the secondary TMP fines, the higher hemicellulose level would be expected to improve bonding, according to Giertz (21). For this reason, Hawes and Doshi questioned Giertz's data.

Stolarz (9) studied fines (-325 mesh) in a recycled, printed colored ledger stock. In comparing handsheets of whole pulp (unfractionated) to those of a fines-free pulp, he found that the whole pulp sheets yielded significantly higher density, tensile strength, and drainage time for formation. Tear strength and porosity were higher for the fines-free sheets. It may be questionable whether these results may be compared to other studies, in light of the facts that fines were only characterized by size, and that no deliberate contaminant removal took place during the repulping process. The potential presence of contaminant particles (i.e. ink) may hold unseen impact on the results of this study.

## METHODS OF FINES CHARACTERIZATION

The most common basis upon which fines are characterized is size. Fractionation of pulp into its respective fractions using a Bauer-McNett classifier or Clark classifier is the most common method of isolating fines by size difference. There has been some indication that the Clark classifier is a faster unit, with better repeatability properties (10). The screen size through which any pulp that passes being called fines varies. Tappi Provisional Method T261 pm-80 designates this screen size as a 200-mesh (76-micron) screen (11). Some researchers have used 150-mesh or 325-mesh screens as well.

Another method for characterizing fines is the centrifugal determination of water retention value (WRV). This test has become widely used since its introduction by Jayme (12). With this test, the affinity of a pulp towards water is determined by centrifuging a sample under standardized conditions. Once the sample has been centrifuged, it is weighed, dried, and reweighed so that WRV expresses the amount of water retained by the pulp calculated as a percent of dry pulp. The following is the equation used to determine WRV:

$$\text{WRV \%} = 100 \times ((\text{wet weight} - \text{o.d. weight})/\text{o.d. weight})$$

The apparatus used to determine WRV is simply a standard laboratory centrifuge using a modified cup. The cup is equipped with a screen inside so that the water can by separated from the fines sample (13). This set-up can be seen in Appendix I.

Various centrifugal forces ranging from 800 to 3000 times the force of gravity have been used. It has been seen that the higher forces produce more reproducible results (12). This force is a function of both the rotational speed and the rotational radius of the centrifuge. Centrifugal force is determined by the following equation (13):

$$F_c = 0.0000284\, RN^2,$$

where $F_c$ = centrifugal force, g's

R = radius of rotation, in.

N = rotation speed, rpm

Thode et al. (13) stated that the centrifugal force used is critical, as too low of a value will fail to overcome the forces of capillary pressure in the interfiber voids and will result in WRV that is higher than the solely intrafiber water responsible for swollen volume. Conversely, too high of a value for Fc will result in fiber distortion and the loss of intrafiber water, showing a falsely low value for water retention value. It is generally agreed upon that fines have a greater WRV than other fractions of a pulp, as a result of the high degree of swelling of fines. According to Thode and Ingmanson (14), the external specific surface of the pulp will increase with swelling. Swelling enables the fines to become more flexible and conformable in a sheet, a condition conducive to improved bonding. Jayme found a straight line relationship between WRV and breaking length developed during refining of a pulp (12).

Compression filtration resistance of a fines mat may also be useful in characterizing fines. Using a pressure cell with a fines cake formed at the bottom, Hawes and Doshi (8) were able to measure filtration velocity through the mat at a constant pressure. Specific filtration resistance was related to the filtrate velocity by:

$U = A\,dP/uWR$, where U = filtration velocity, cm/s

A = area of fines pad, $cm^2$

dP = pressure drop across pad, $g/cm\text{-}s^2$

u = filtrate viscosity, g/cm-s

W = mass of fines, g

R = filtration resistance, cm/g

The variation of filtration resistance with P is an indirect measure of compressibility of the fines. This is shown as

$R = a\,dP^b$, where a = filtration resistance of uncompressed fines mat

b = compressibility constant

A higher value of b indicates a higher compressibility of the fines. The compressibility of the fines is an important factor regarding their participation in bonding. Ingmanson and Andrews (15) found that the level of filtration resistance of a whole pulp was largely determined by the amount of fines present, mainly due to the high surface area of the fines as compared to the remainder of the pulp.

Scanning electron microscopy has also been widely used to gain visual interpretations of the qualities of fines material. This method yields information regarding size, shape, and surface properties of the fines material.

Analysis of the chemical composition of the fines is also useful in the characterization of fines. Hawes and Doshi (8) use percent lignin and percent carbohydrates determination from Effland (16) and Tappi Method T249 pm-75, respectively.

Other potential methods of characterizing fines include settling rate in water, light scattering ability, or image analysis. Image analysis can yield both size distributions of the fines fraction and shape factors for the fines themselves.

Origin of fines is also used to help identify the properties of fines matter. This deals with the terms primary and secondary fines. Primary fines are those that are present in unrefined pulp. These fines consist of parenchyma cells, vessel segments, film-like fragments derived from the middle lamella or outer cell wall layer, and amorphous particles of mineral origin (17)(18). It is generally agreed upon that primary fines are not conducive to good fiber bonding in a sheet. Upon SEM analysis, Hawes and Doshi (8) found primary fines from unbleached kraft, TMP, and recycled kraft pulps to be largely made up of flake-like, chunky particles. By virtue of their relatively low specific surface area, it can be seen that these fines would not lead to good bonding potential. They also found these fines to be much less

compressible than their secondary counterparts, inhibiting their ability to conform in a sheet of paper. Secondary fines are those fines that are produced during refining operations. As summarized by Mancebo et al. (19), these fines are mainly fibrillar in nature, resulting from the partial removal of the primary and secondary walls of the fibers. Hawes and Doshi (8) observed this fibrillar nature in their study of fines. Many have found that the greater specific surface of the fibrillar, secondary fines is the reason for their better bonding ability (20)(21).

## PRESENTATION OF PROBLEM

The problem that has become evident in most of the cited literature is the lack of thorough characterization of fines, with subsequent conclusions drawn about the nature of these fines based on the limited characterizations. For the most part, size was the standard method of characterization of fines material. This essentially leaves many fines characteristics that may have considerable impact on sheet properties unaddressed.

The objective of this project was to characterize fines by more than just size. Of interest were water retention values, compression filtration resistance values, size distributions and shape factors of the fines fraction, and light scattering ability of the fines. In characterizing fines in these ways, a more complete picture of the fines effects on sheet properties can be drawn.

# EXPERIMENTAL

## EXPERIMENTAL DESIGN

The experimental procedure in this project consisted of pulp selection and preparation, fines fraction isolation, handsheet production and testing, and fines characterizations.

In choosing a wood source, softwood was selected because it has a greater ability than a short-fiber hardwood to develop strength properties. There was also a greater size difference between the fines fraction and the longer fiber fractions of the pulp. Southern yellow pine was selected as a fiber source as a result of the ability to get both wood chips and pulps made from these chips from the same supplier.

The pulps studied in this project were TMP, unbleached kraft, and bleached kraft. These three very different types of pulp were selected on the basis of their ability to show profoundly different fines characteristics.

Once the fines had been isolated from the other fiber fractions of a given pulp, they were evaluated for the following properties: size, water retention value, compression filtration resistance, size distribution, light scattering ability, and drainability. These properties, when considered together, gave a clear characterization of the fines which was related to their performance in a sheet of paper.

Handsheets were made containing various levels of fines and tested for the following sheet properties: density, opacity, brightness, scattering coefficient, tensile index, tear index, and burst index. These tests showed the effects that the fines have on the sheet properties.

## EXPERIMENTAL PROCEDURE

### Pulp Preparation

For preparation of the TMP, yellow pine chips at 52% moisture were pulped in the WMU Sunds Defibrator, with a throughput of 127 lb/hr of dry pulp. The pulp was then refined in the Claflin conical refiner at 3.2% consistency to a final freeness of 165 ml CSF.

In preparing the unbleached and bleached kraft pulps, pulp was obtained from the same source as the wood chips. These were commercial pulps furnished by Union Camp Corporation in Franklin, Virginia. Each of the pulps was refined in a Claflin refiner to 530 ml CSF and 280 ml CSF for the unbleached and bleached pulps, respectively. Refining consistencies were 3.2% and 2.8%, respectively.

### Fines Isolation

Following refining, the TMP, unbleached kraft, and bleached kraft were diluted to 0.75, 0.65, and 0.625% consistency, respectively. Fines were removed from each of the pulps using

the WMU Float-Wash unit equipped with an 80 micron screen. A diagram and outline of operation can be seen in Appendix II. Flow rate to the unit for each pulp was approximately 100 gpm, with 25 inches of water vacuum on the accept side of the Float-Wash unit. The fines-free pulp rejected in the Float-Wash was saved for handsheet preparation. The fines were collected in a 1200-gallon chest and allowed to settle for 24 hours. Water was then pumped from the surface of the fines suspension. The remaining fines were then filtered through a muslin cloth bag to obtain a manageable volume of fines. This final consistency ranged from 2% to 6.5%.

Characterization of Fines

Fines were photographed in order to gain both qualitative and quantitative information about the nature and size of the fines material. Fines at 0.5% consistency were dyed with direct black dye in order to increase contrast for photography. The fines were heated to approximately 140 degrees F., with 10% addition by weight of pulp of NaCl to aid in fixing the dye to the fines. The fines were then diluted to 0.1% consistency and placed on a microscopic slide with a cover glass. Photographs were taken of the wet fines using a Nikon microscope and camera apparatus (courtesy of James River Corporation, Kalamazoo, Michigan). Pictures were taken at 40X, 100X, and 200X magnification levels. These pictures were then viewed to determine the general physical nature of the fines.

Size distributions for the fines component of each pulp were determined using the Kajaani FS-100 Fiber Analyzer. Fines samples were prepared at 0.001% consistency, with over 5000 particles counted for each type of fines.

Centrifugal water retention values were determined using a laboratory centrifuge with specially designed cups. These cups can be seen in Appendix I. Fines in water suspension at 0.43% consistency were poured into the cups and allowed to gravity-drain for 1-1/2 hours. Samples for each pulp type were then centrifuged in quadruplicate for 30 minutes at a centrifugal force of 900 times the force of gravity. The pads were then weighed, dried at 105 degrees C. for 24 hours and reweighed.

Tests to determine the drainability of the fines were performed in the British Sheet Mold. One oven-dry gram of fines at 0.014% consistency (6950 ml water) was drained onto the 200-mesh sheet mold screen. The time for all of the free water to drain from the fines was measured using a stopwatch. Ten determinations were made for each pulp type.

Compressibility of the fines was determined using the apparatus illustrated in Appendix III. Fines at 0.001% consistency were poured into micropore a filter assembly using a 9.079 $cm^2$. suction area. Vacuum was drawn through the filter using a vacuum pump. The fines suspension was initially dewatered at a vacuum level of 10 inches Hg. Distilled water was then poured into the funnel and drained at vacuum

levels of 10, 15, 20, 25, and 28 inches Hg. The time to drain 50 ml of water through the pad at each vacuum level was recorded.

## Handsheet Production

Handsheets were initially made on the Noble and Wood Handsheet machine. However, the TMP sheets could not be easily removed from the 150-mesh screen without damage to the sheets. For this reason, all sheets were made on the British sheet mold, following Tappi Standard T205 om-81 (23). Sheets were made at the following fines levels: 0, 7, 15, 22, and 30% fines. Target grammage of the sheets was 58 g/m$^2$. Distilled water was used to form all handsheets to avoid coloration problems associated with iron present in the tap water. A 200-mesh screen was used for forming the sheets. Any fines that may have escaped through the wire were considered negligible, as the sheets formed quickly after the start of the drainage. The sheets were couched off the wire using a single sheet of wetted blotter paper, pressed, and then dried on the Noble and Wood dryer. The sheets were then placed in the standard conditioning room (73 degrees F., 50% relative humidity) until testing.

## Physical Testing of Handsheets

The handsheets were first tested to determine opacity and brightness, using Tappi Standards T425 om-86 and T452 om-87, respectively (24)(25). Ten tests were taken on ten different

sheets for each of these properties. Scattering coefficients for sheets at each fines level were determined using equations found in T425 om-86.

Tensile index, tear index, and burst index were determined using Tappi Standards T494 om-81, T414 om-82, and T403 om-85, respectively (26)(27)(28). For tensile, determinations were made on ten samples from ten different sheets. Ten determinations for tear index were made from five different sheets of paper. Ten determinations of burst index were made on five sheets, with five being taken on the wire side and five taken on the felt side of the sheet.

Caliper was measured using Tappi Standard T411 om-84 (29). A motor-driven micrometer was used to test ten sheets. From this information, density of the paper was calculated.

## RESULTS PRESENTATION AND DISCUSSION

### PROPERTIES OF FINES

Photo-micrographs of bleached kraft fines are shown in **Figures 1, 4,** and **7.** From these pictures it is seen that the bleached kraft fines are quite fibrillar in nature. These fines originate from the primary and secondary walls of the fibers. It is also evident that the fines tended to flocculate into bunches of fines in water suspension. This condition was also seen by Hsu (31). This can be explained by the large specific surface area of the fines and by the extreme amount of bound water at the surface of the fines, as was found by Giertz (7). These conditions will tend to promote hydrogen bonding and thus flocculation of the fines in suspension.

Unbleached kraft fines are shown in **Figures 2, 5,** and **8.** These fines tend to be more of a mix of primary and secondary fines than with the bleached kraft fines. This can be seen by the mix of flake-like material of primary fines with the more fibrillar secondary fines. Comparable results were documented by both Hawes and Doshi (8), and Mancebo et al. (19).

**Figures 3, 6,** and **9** illustrate the TMP fines. These fines appear quite flake-like and chunky, with very little fibrillar material present. These fines resulted from both pulping and secondary refining.

The contrast of these pictures was still not adequate to allow for analysis with the image analyzer. For this reason,

only qualitative information could be obtained from the photomicrographs.

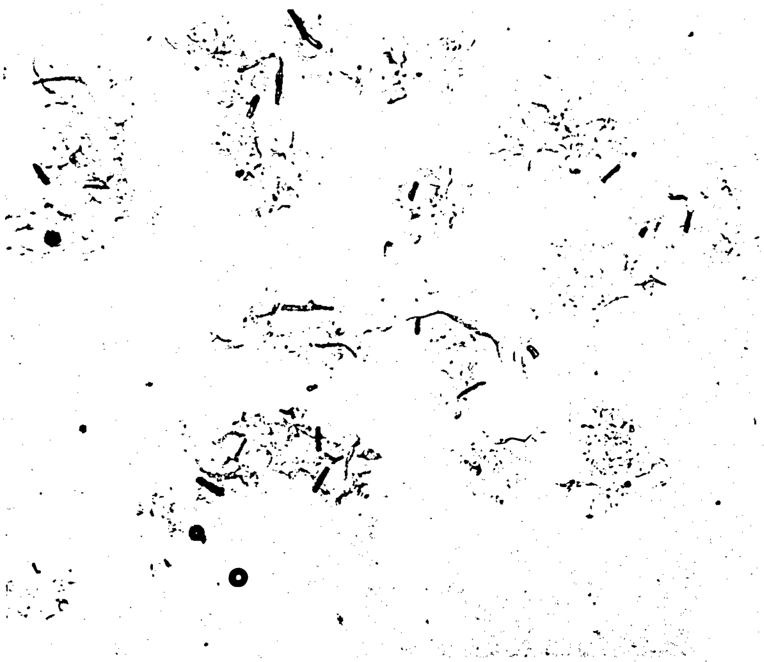


**Figure 1:** Bleached Kraft fines at 40X magnification

**Figure 2:** Unbleached Kraft fines at 40X magnification

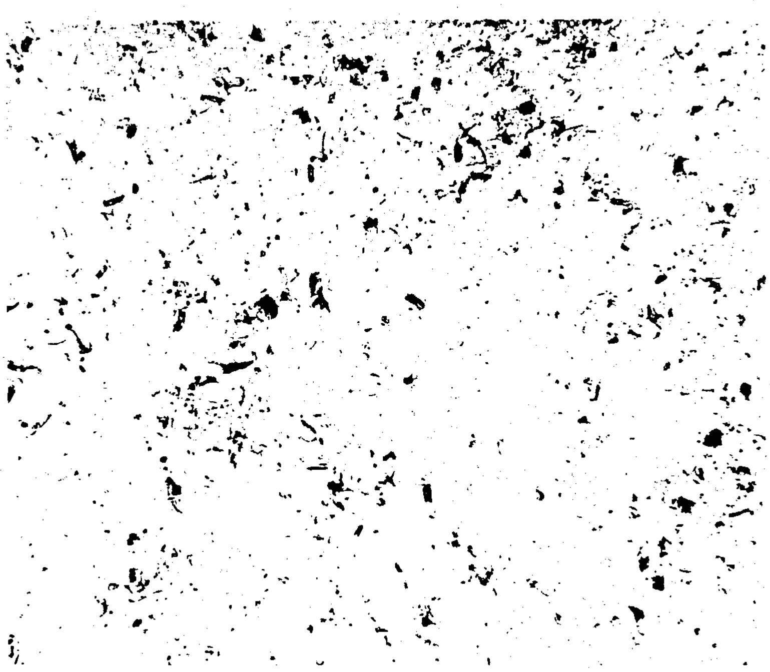


**Figure 3:** TMP fines at 40X magnification

**Figure 4:** Bleached Kraft fines at 100X magnification

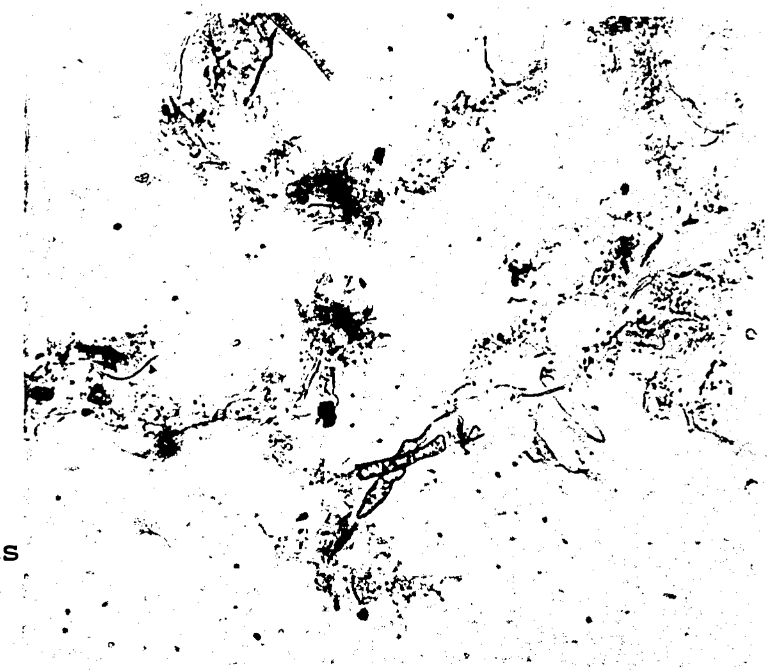


Figure 5: Unbleached Kraft fines at 100X magnification

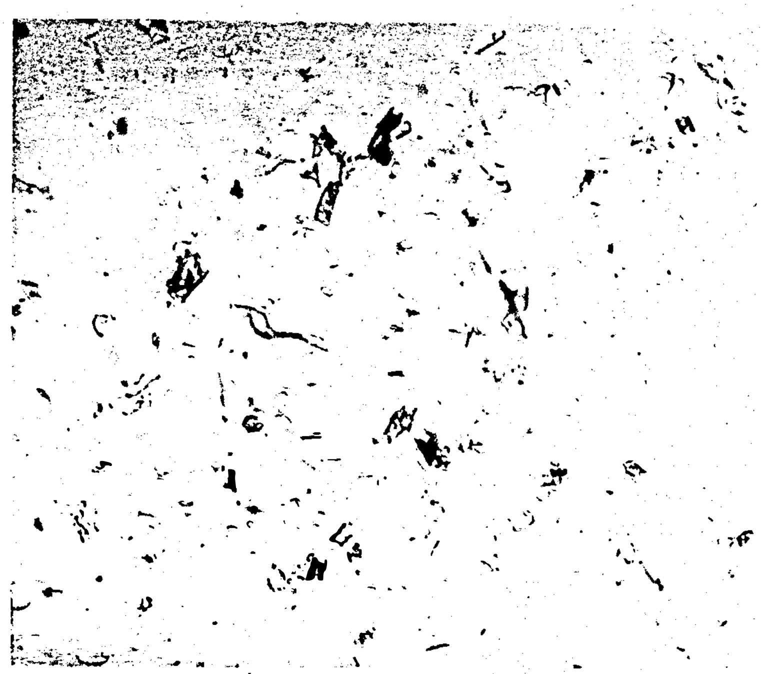


Figure 6: TMP fines at 100X magnification

**Figure 7:** Bleached Kraft fines at 200X magnification

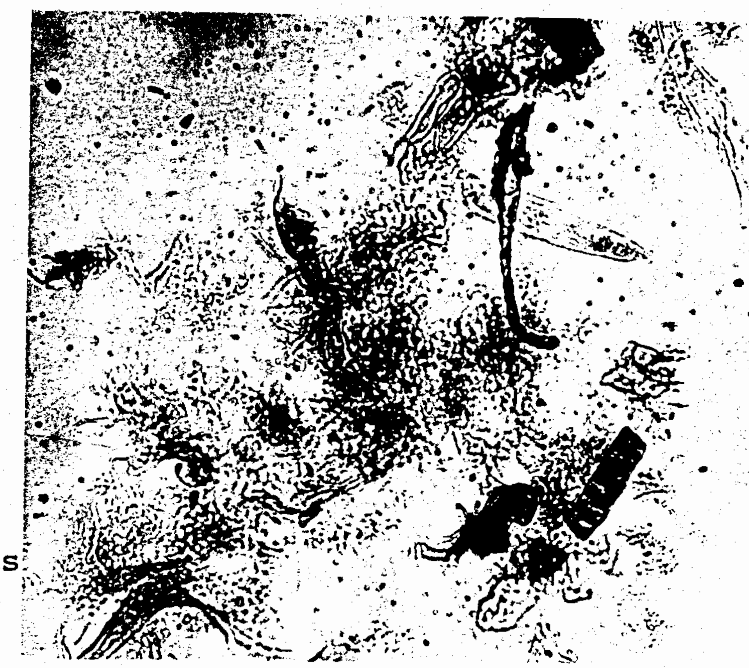


**Figure 8:** Unbleached Kraft fines at 200X magnification

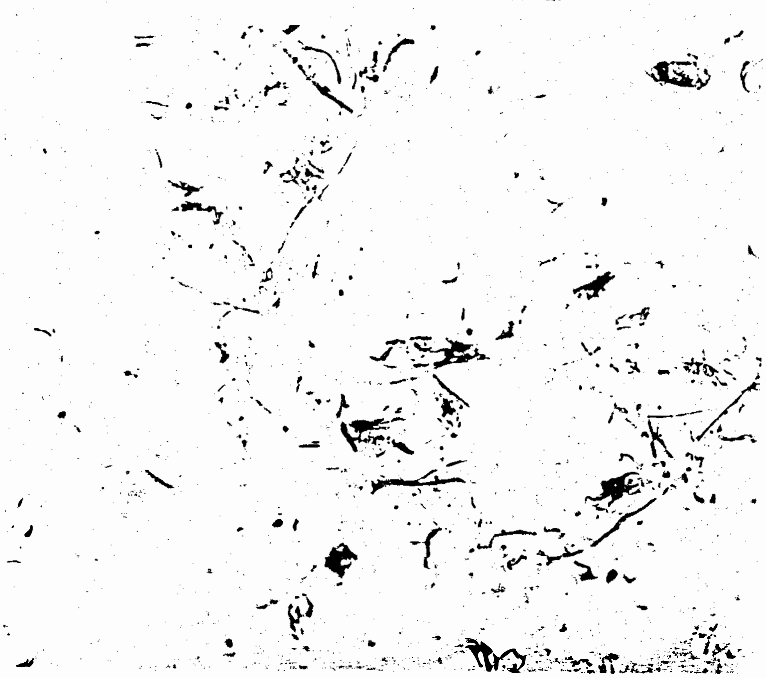
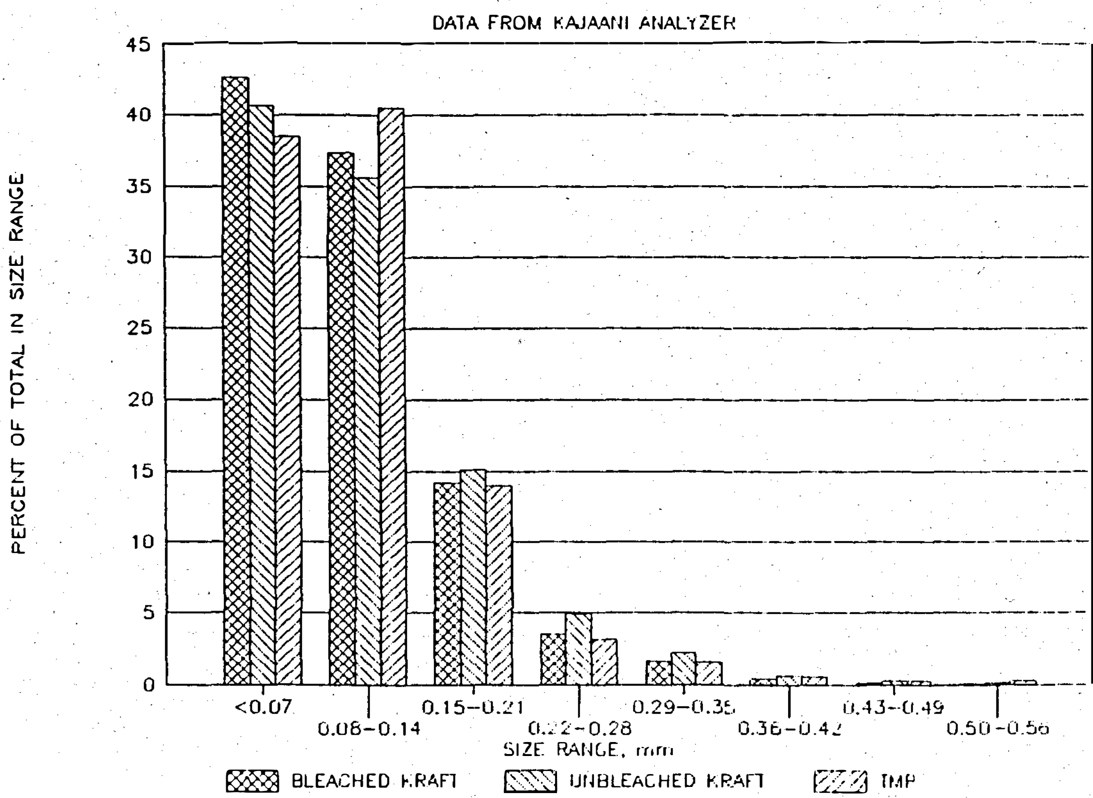


**Figure 9:** TMP fines at 200X magnification

**Figure 10** illustrates results from length analysis with the Kajaani Fiber Analyzer. In the case of each type of fines, it can be seen that over 90% of the fines material is less than 0.22 mm in length. This method is limited by the fact that the smallest measured size is 0.07 mm, and it is quite likely that a portion of the fines material is much smaller than this. Data from the Kajaani analysis can be seen in Appendix IV.

**FIGURE 10: FINES SIZE DISTRIBUTIONS**




Results of centrifugal water retention tests can be seen in **Figure 11.** As expected, the bleached kraft fines proved to have the greatest affinity for water, followed by the unbleached kraft

and the TMP. These results agree well with the conclusions drawn regarding the origin and composition of each type of fine. In work done by Jayme (12), it was found that bleached kraft pulps had a lower water retention potential than unbleached kraft pulps. While this is not in agreement with the results found here, it should be noted that Jayme was using whole pulps and study of the fines themselves was not performed. The bleached kraft fines, made up primarily of hemicellulose and cellulose, have a natural affinity for water. The unbleached kraft and TMP fines contain lignin, which is less hydrophillic than hemicellulose and cellulose, resulting in lower water retention values. This lignin would also tend to restrict swelling of the fines due to its cross-linked, stiff nature. Water retention data is shown in Appendix V.

**FIGURE 11: CENTRIFUGAL WRV FOR FINES**

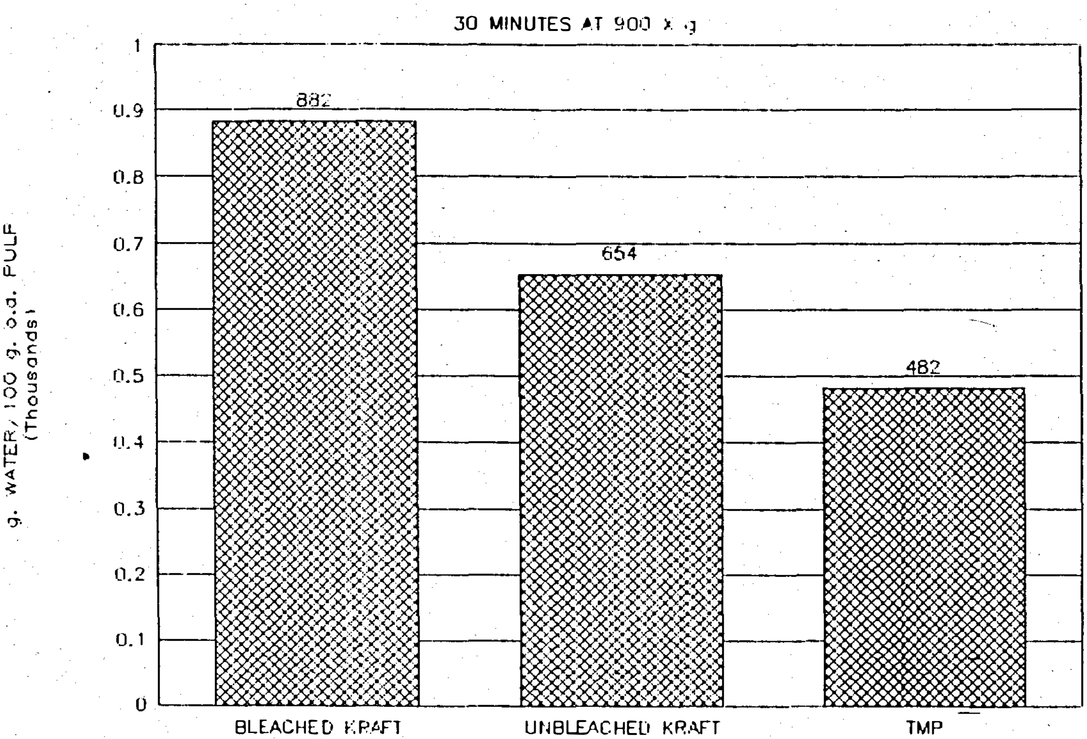


**Figure 12** illustrates results from the drainage tests in the British Sheet Mold. Unexpectedly, the unbleached kraft fines showed far greater drainage times than the bleached or the TMP fines. The most probable theory to explain this relates to the greater mix of particle shapes and sizes seen in the photomicrographs. With a wider array of sizes, the voids on the sheet being formed are more easily sealed, allowing very little flow through the mat. The bleached kraft and TMP fines may have less of an ability to fill in these voids. Drainage data is listed in Appendix VI.

FIGURE 12: DRAINABILITY OF FINES

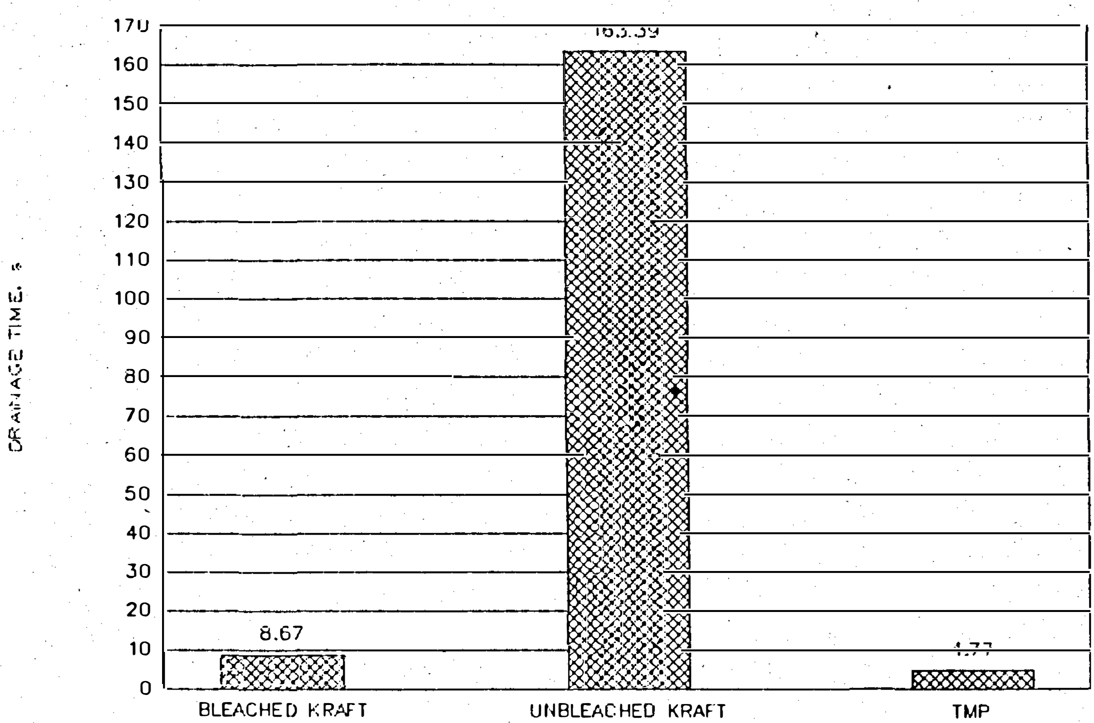


**Figure 13** illustrates the effects on drainability of water through the fines mats at various levels of differential pressure. As was seen with the drainage tests in the British Sheet Mold, the unbleached kraft fines drained the slowest, followed by the bleached kraft and TMP fines. Using the equations used by Hawes and Doshi (8), compressibility values for each type of fines were determined. As seen in **Figure 13a**, the TMP fines were calculated to be the most compressible, followed closely by the unbleached kraft and the bleached kraft. This is not the expected result. One would expect to see the bleached kraft as the most compressible, followed by the unbleached kraft and then the TMP. The tests for compressibility were made between 10 and 15 inches of water vacuum on the fines. For the TMP, the average times to drain 50 ml of water at both 10 and 15 inches were determined to be statistically equal using a Z-test for determining differences between two population means. As there is statistically no difference between the resistance of the uncompressed and the compressed mat, it could be stated that the TMP fines were virtually incompressible. At the same levels of differential pressure, average times for the bleached and unbleached kraft fines were determined to be statistically inequivalent using the same test. Calculations for these tests can be seen in Appendix VII. In the case of the unbleached fines, the results of the

compressibility test may be somewhat misleading. As with the drainability tests in the British Sheet Mold, it is believed that what may at first be interpreted as compressibility may in fact be resulting from the effects of the wide mix of particle sizes present. There is the possibility that these particles are not really compressible, but mobile in the mat, moving into voids as more pressure is applied, giving the effect of compressibility.

*Figure 13 : EFFECT OF PRESSURE ON DRAINABILITY*

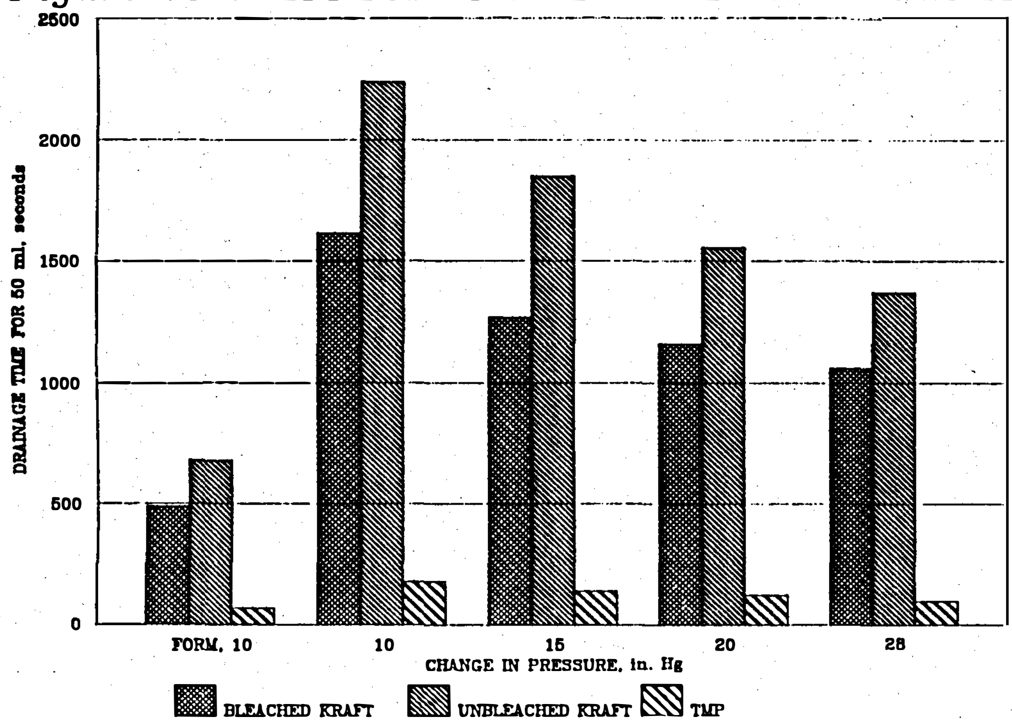
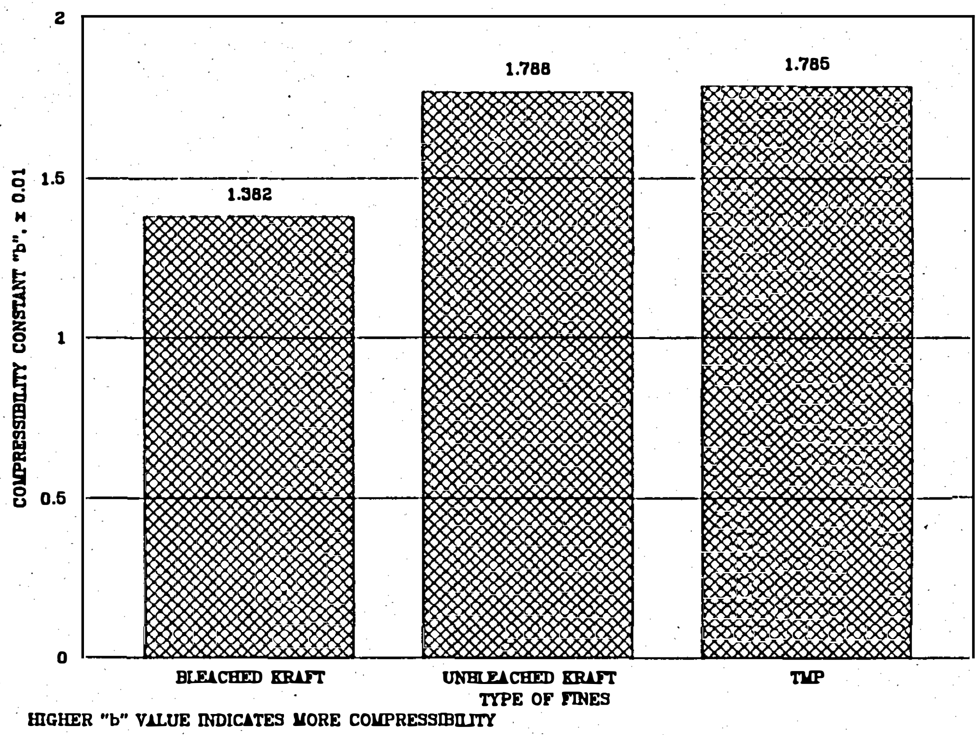


*FIG. 13a: COMPRESSIBILITY OF FINES*




PROPERTIES OF HANDSHEETS

Graphs from the following section of the results start on page 35.

Density

As can be seen in **Figures 14, 15,** and **16,** as fines levels increased, so did densities for bleached kraft, unbleached kraft, and TMP. This is the expected result, as the fines have the ability to fill in voids in the sheet, making a more dense network. The high bonding area contribution of the fines also

serves to compact the final sheet structure, resulting in higher density. These increases in densities will serve as part of the basis for the fines' contributions to the development of other sheet properties. Raw data used to determine density is listed in Appendix VIII.

<u>Opacity</u>

**Figures 17, 18,** and **19** illustrate the effects of fines on opacity of the paper. With the bleached and unbleached kraft fines, opacity decreased with the addition of fines, as expected. As the fines provide for a denser, more closely bonded sheet, there were fewer surface areas to scatter light, thus lowering opacity. Opacity data is seen in Appendix IX. **Figures 20** and **21** show the decreases in scattering coefficients in the sheets as fines levels increased, supporting the results of the opacity tests. **Figure 22** shows the decreasing scattering coefficient of the TMP sheet with the addition of fines. This would lead one to expect a decrease in the opacity of the sheet also. However, **Figure 19** shows increasing opacity with fines addition for the TMP sheet. This may be explained by considering the color of the fines themselves. During the processing steps of the fines, they may have picked up iron from the water, giving color to the fines. This color may be responsible for the increase seen in opacity, as these colored iron compounds absorb light, increasing the measured opacity. Appendix X lists scattering coefficient data.

Brightness

**Figures 23** and **24** illustrate the effect of fines addition on brightness of the sheets for bleached kraft and TMP. Brightness tests were not performed on the unbleached sheets, as brightness in rather irrelevant for grades made from unbleached kraft. As expected, the brightness of the bleached kraft sheets decreased with the addition of fines. This comes as a result of increased bonding in the sheet, leaving less surface areas in the sheet to scatter light. The brightness of the TMP sheets showed an overall decrease with fines addition. This may be caused by both the decreased scattering coefficients and the color of the fines as mentioned in the discussion of opacity. **Figures 23a** and **24a** show the effects of fines level on absorption coefficients of the bleached kraft and TMP sheets, respectively. Absorption coefficients for both types of pulp increased as fines level increased. This is reflected in the losses in brightness with increasing fines levels seen for each type of pulp. The TMP sheets possessed far greater absorption coefficient values than the bleached kraft. This can be attributed to the colored components in the TMP pulp. Again, this is seen in the differences in brightness values between the bleached kraft and the TMP sheets. Data for brightness is seen in Appendix XI.

Tensile Index

**Figures 25, 26,** and **27** illustrate the effects of fines addition on sheet tensile indexes. For each type of pulp,

tensile index increased as the level of fines in the sheet was increased. This can be explained again by the improved bonding in the sheets afforded by the high surface areas of the fines. With the addition of fines also comes better distribution of forces in the sheet during the tensile testing procedure. Appendix XII lists tensile index data.

## Burst Index

As seen in **Figures 28** and **29**, the burst index of both the bleached and unbleached kraft sheets increased as fines level increased. Again, this can be explained by improved bonding in the sheet due to the fines. For the bleached kraft fines, the gradual decrease in strength above 22% fines may be explained in terms of the length of the fibers in the sheet. The fines are much shorter than the fibers, allowing for less elongation in the sheet before rupture. Above 22% fines, it appears that a point has been reached where the sheet's ability to stretch has been degraded, thus breaking under less pressure. Burst tests could not be performed on the TMP sheets, as they were too weak to register reliable values during testing. Data for burst index can be seen in Appendix XIII.

## Tear Index

**Figures 30, 31,** and **32** illustrate the effects of increased fines levels on the force required to tear sheets of each type of

pulp. As expected, tear index decreased with fines addition in the bleached kraft sheet. This may be explained by the idea that increased bonding due to the presence of fines allows more long fibers in the sheet to break, which requires less work than breaking the bonds and pulling these long fibers from the sheet. This in turn reduces the amount of force required to tear the sheet. In **Figure 31**, the slight increase in tear index between 7 and 15% fines for the unbleached kraft sheet may be explained by the more uniformly formed sheet at 15% fines yielding better stress distribution in the sheet, thus increasing the tear slightly. This appears much like a beater curve in the development of strength properties. The TMP sheets were by far the weakest sheets, attributed to by its short, chunky fines. The increase seen in tear index may again be explained by possibly better stress distribution in the sheet. Appendix XIV lists tear index data.

FIGURE 14: **EFFECT OF FINES CONTENT ON DENSITY BLEACHED KRAFT FINES**

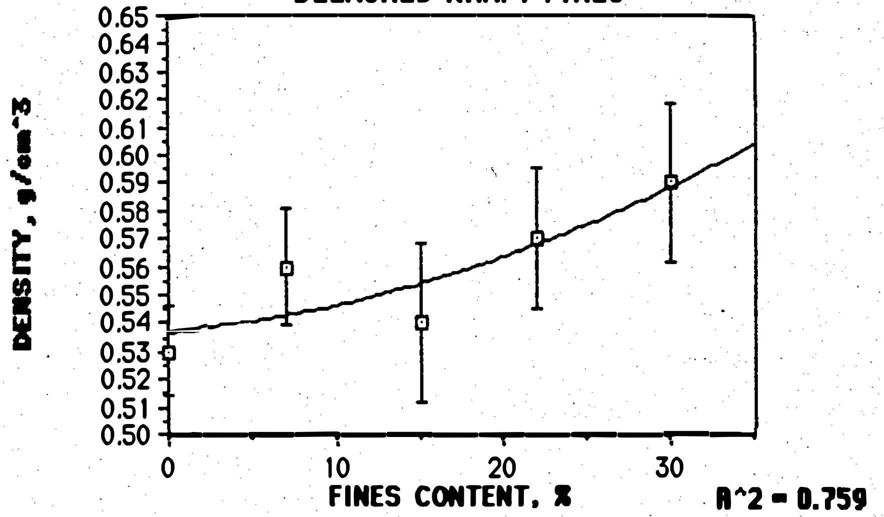



FIGURE 15: **EFFECT OF FINES CONTENT ON DENSITY UNBLEACHED KRAFT FINES**

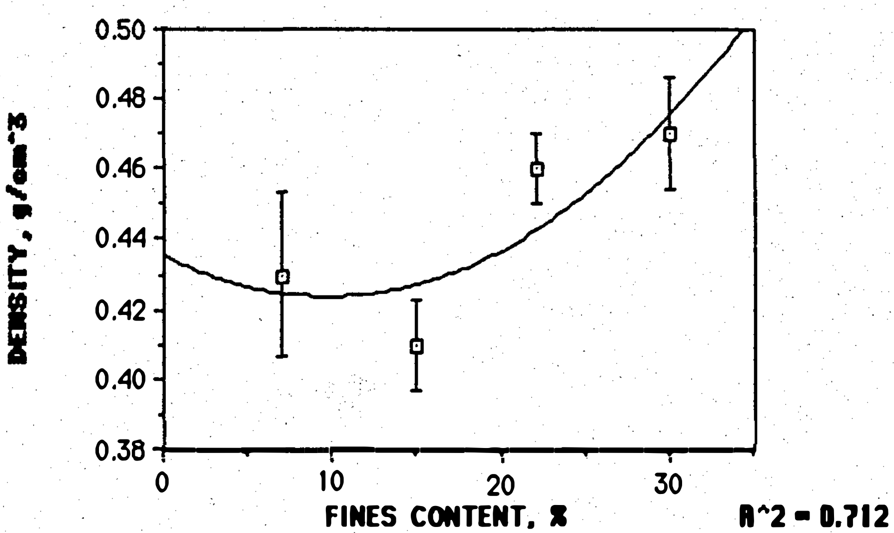



FIGURE 16: **EFFECT OF FINES CONTENT ON DENSITY TMP FINES**

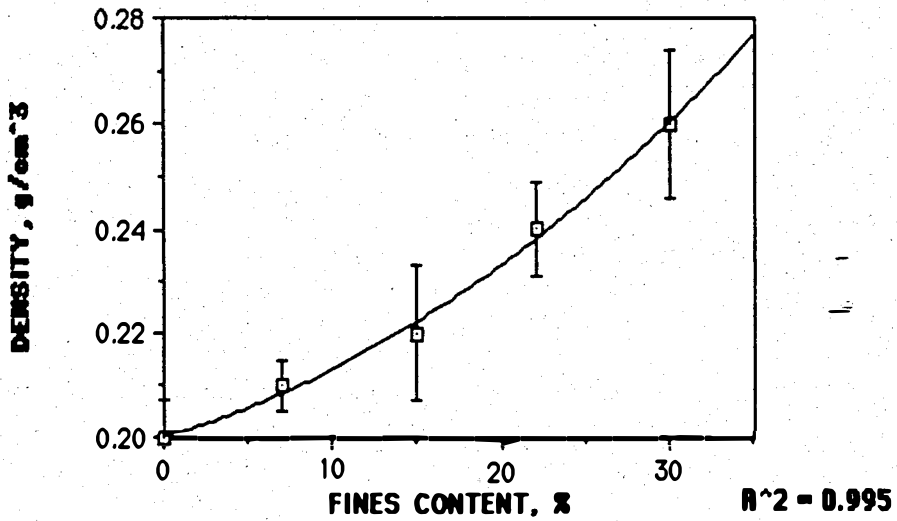


FIGURE 17:

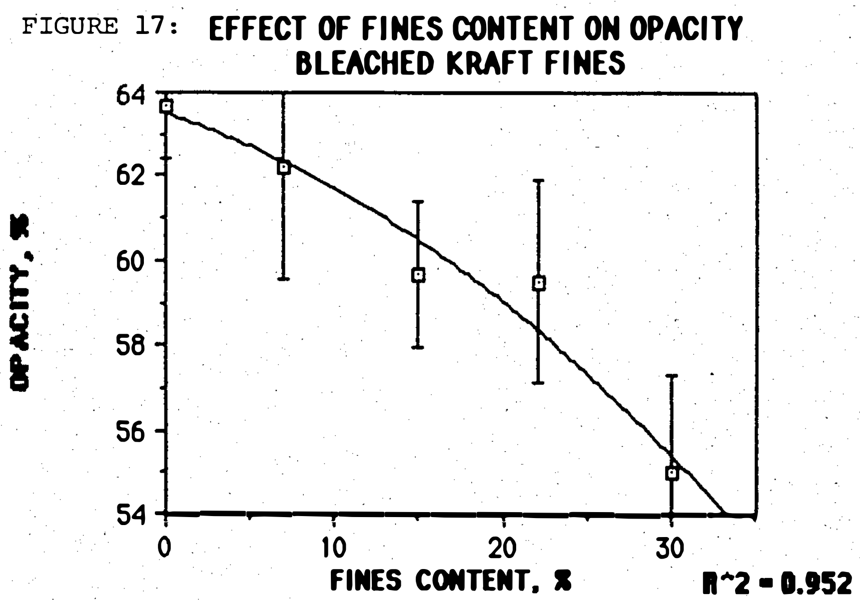



FIGURE 18:

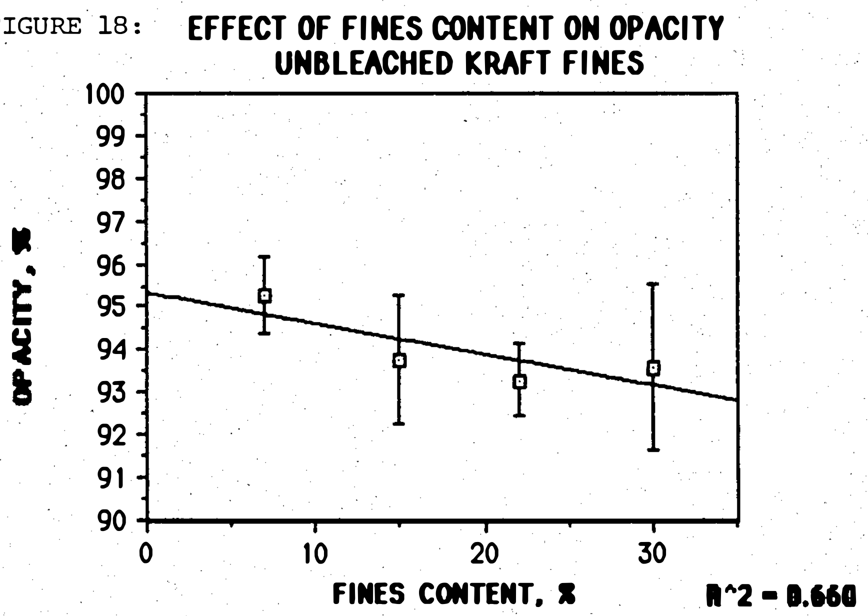



FIGURE 19:

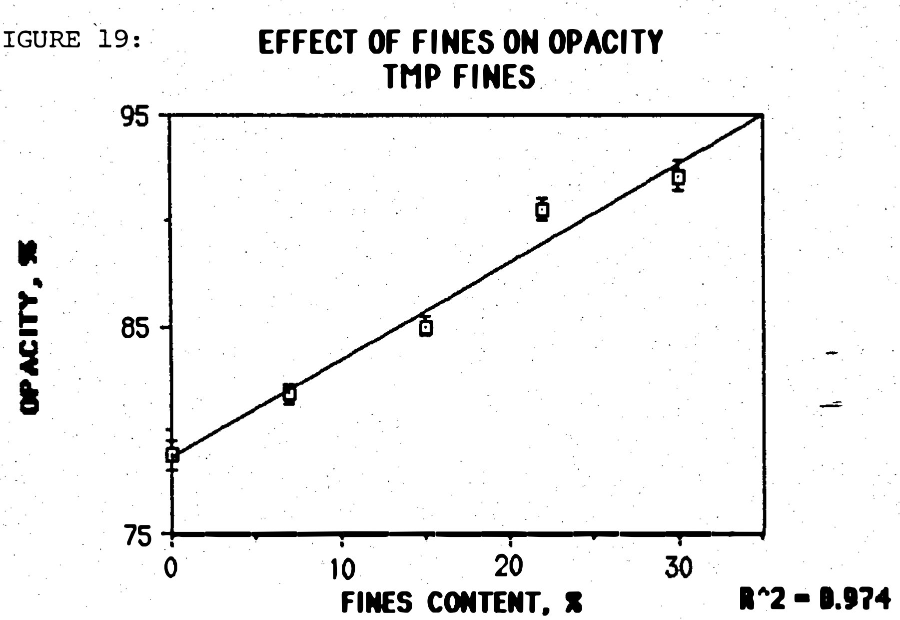


FIGURE 20:

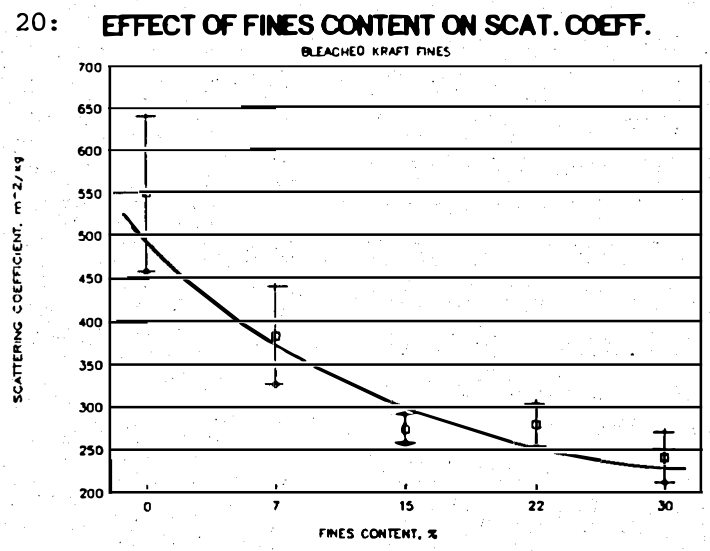



FIGURE 21:

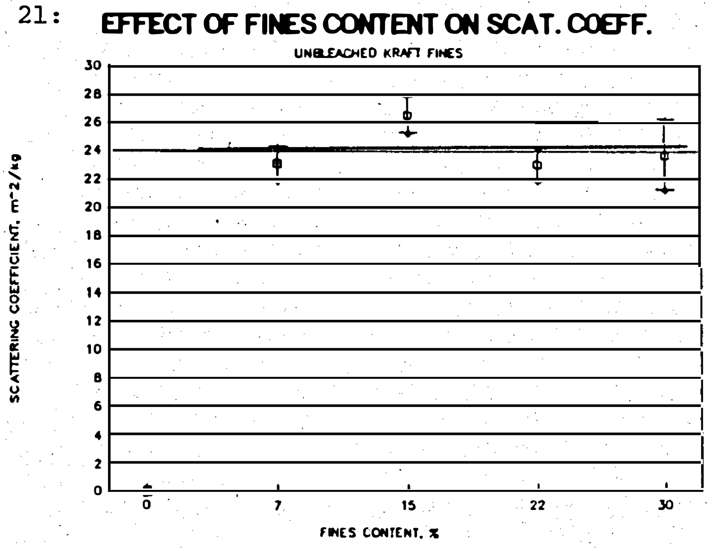



FIGURE 22:

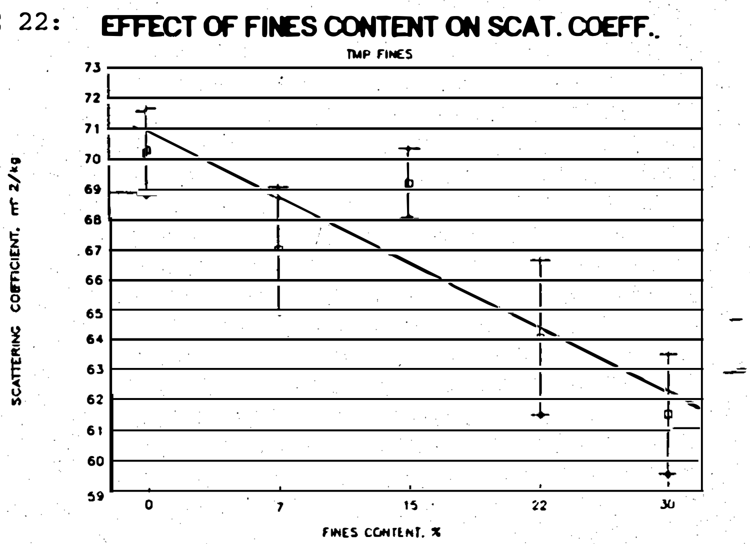


FIGURE 23:

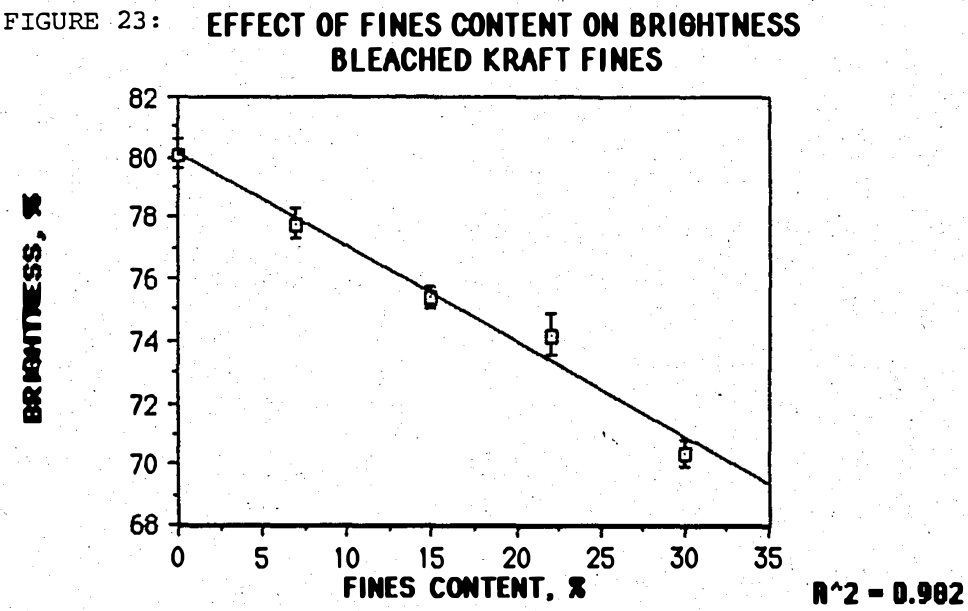
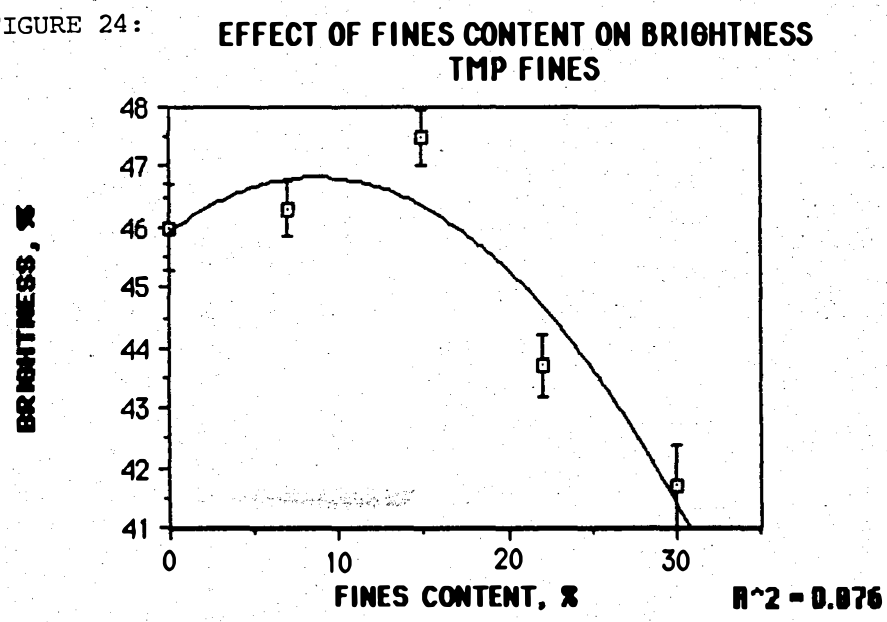
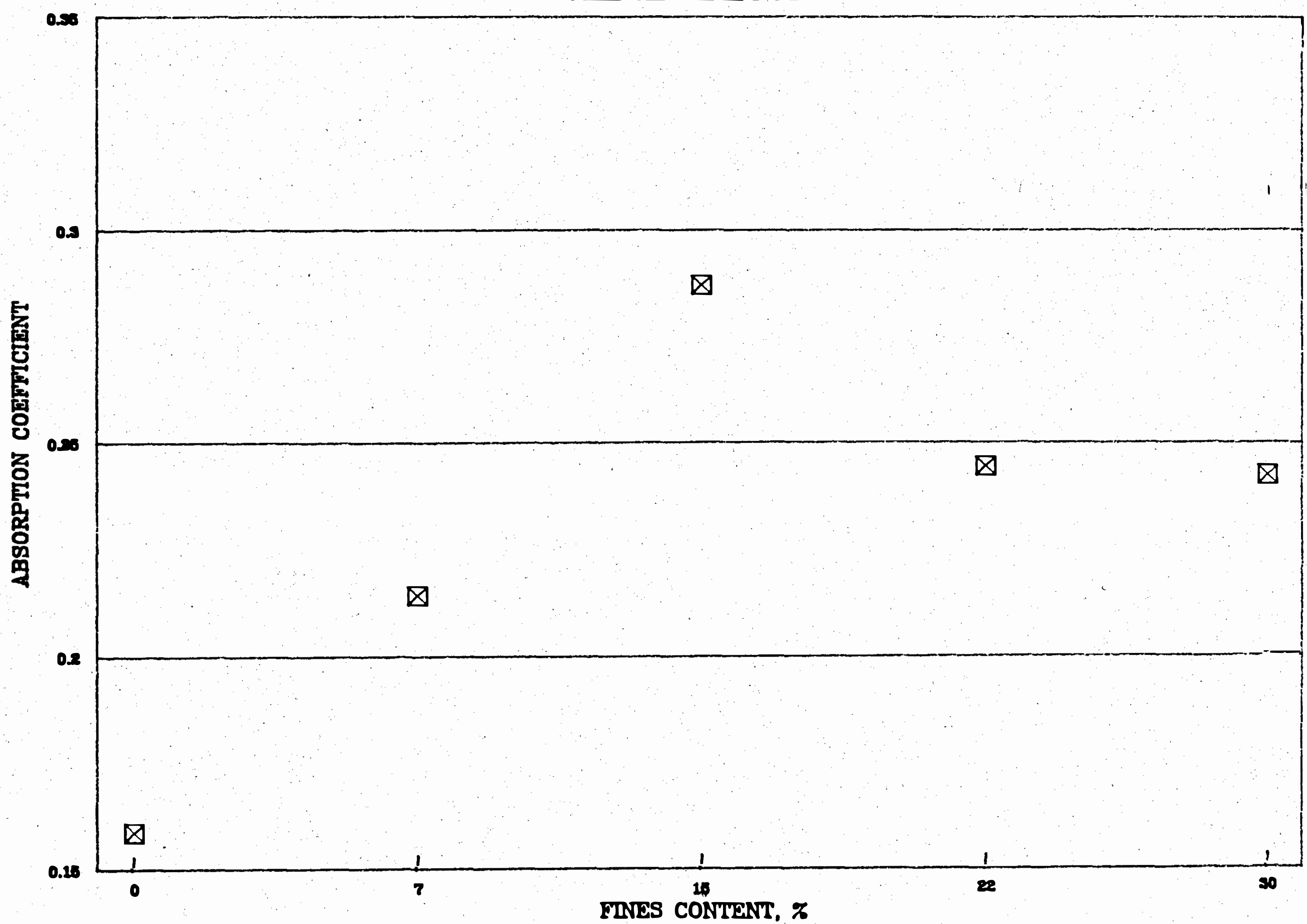



FIGURE 24:



# *FIGURE 23a: ABSORPTION COEFFICIENT*

**BLEACHED KRAFT FINES**



# *FIGURE 24a: ABSORPTION COEFFICIENT*

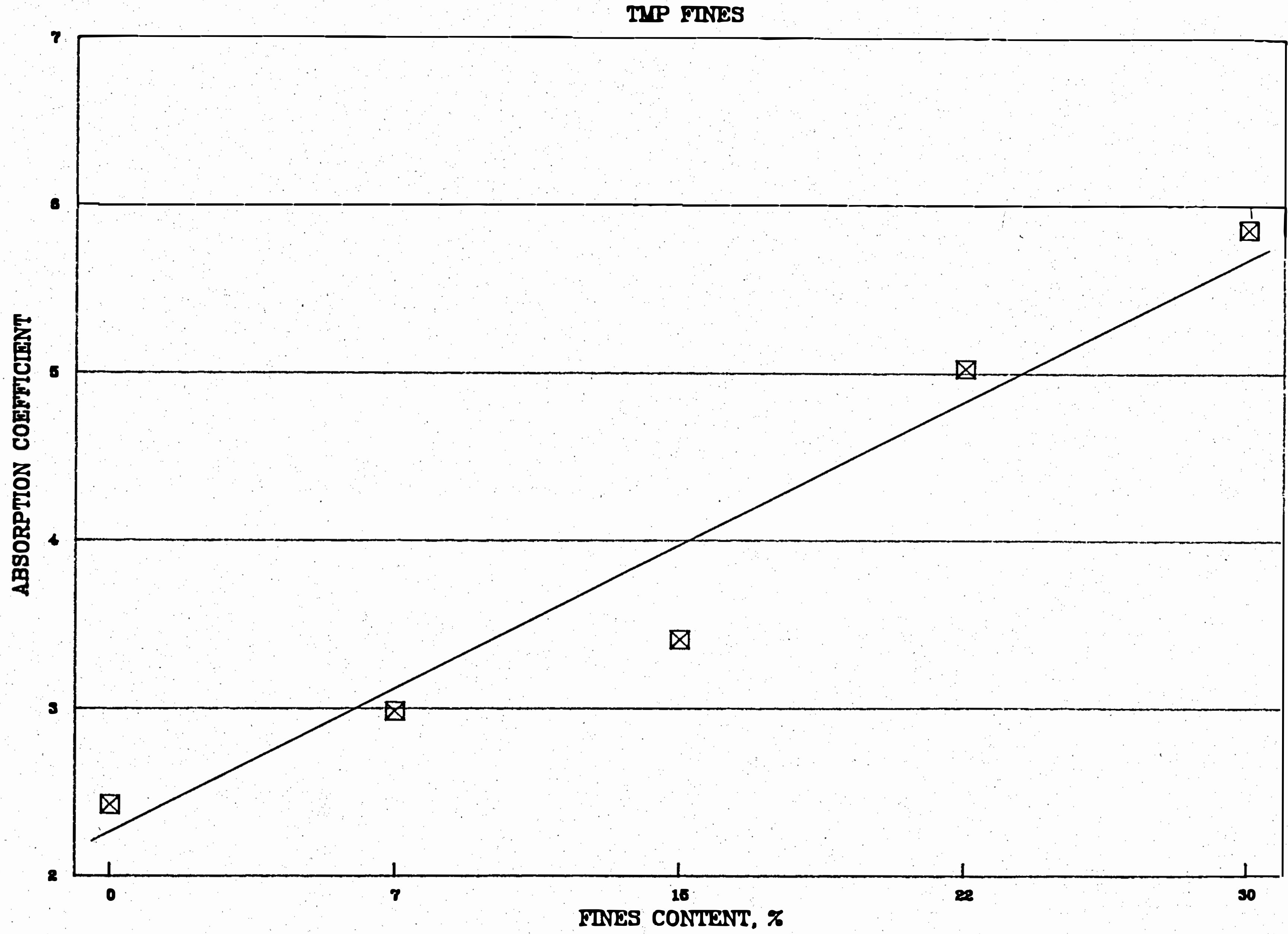


FIGURE 25: EFFECT OF FINES CONTENT ON TENSILE INDEX
BLEACHED KRAFT FINES

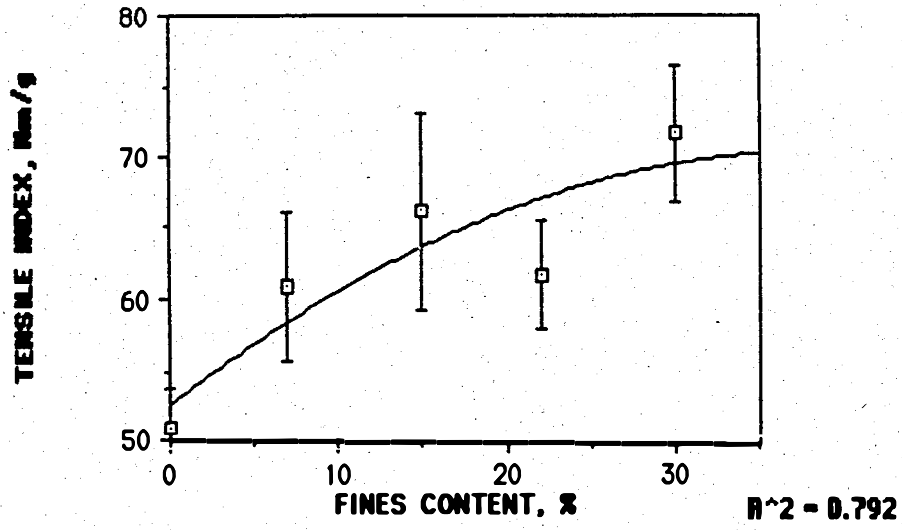



FIGURE 26: EFFECT OF FINES CONTENT ON TENSILE INDEX
UNBLEACHED KRAFT FINES

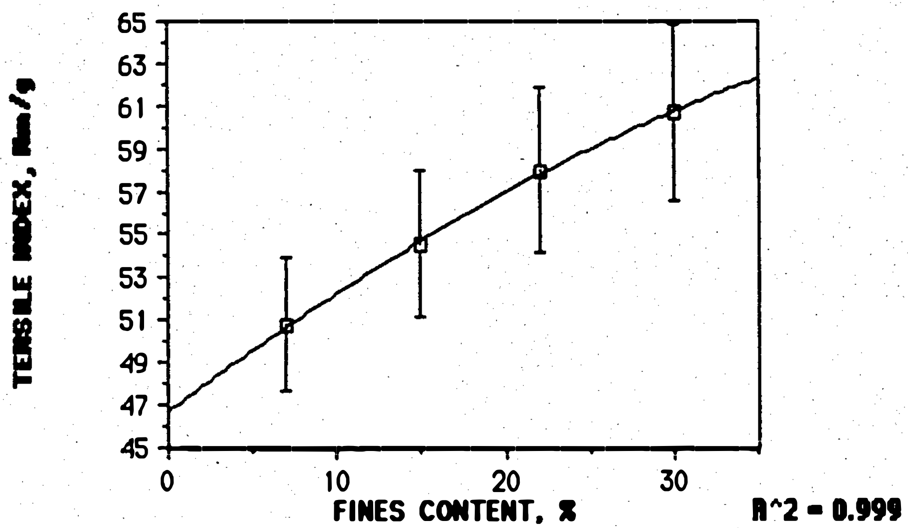



FIGURE 27: EFFECT OF FINES CONTENT ON TENSILE INDEX
TMP FINES

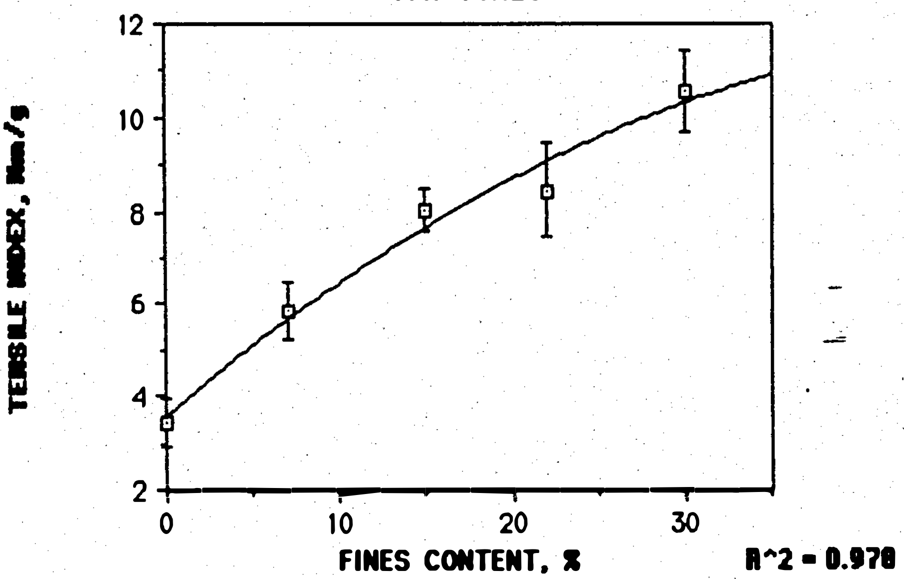


FIGURE 28: EFFECT OF FINES CONTENT ON BURST INDEX BLEACHED KRAFT FINES

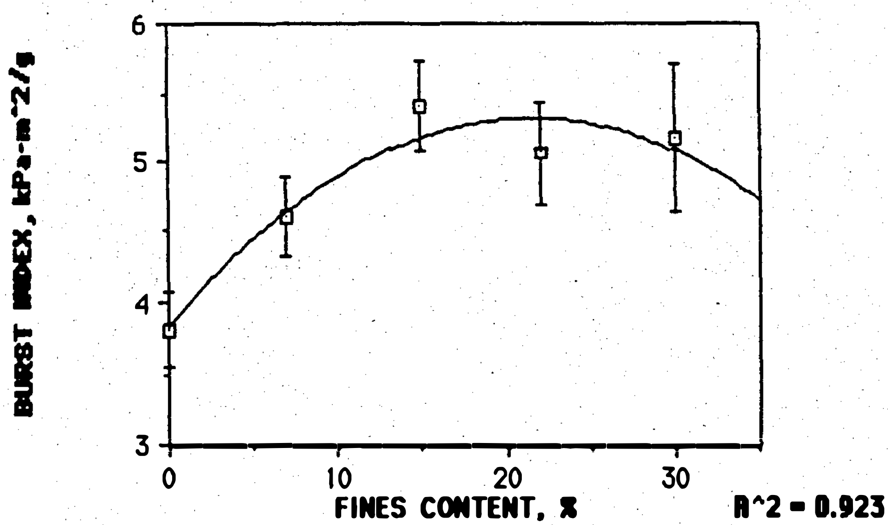



FIGURE 29: EFFECT OF FINES CONTENT ON BURST INDEX UNBLEACHED KRAFT FINES

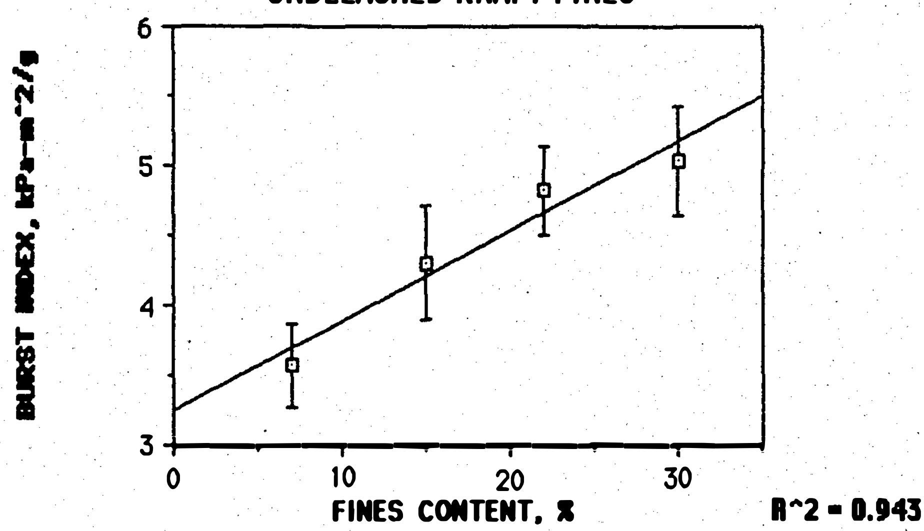
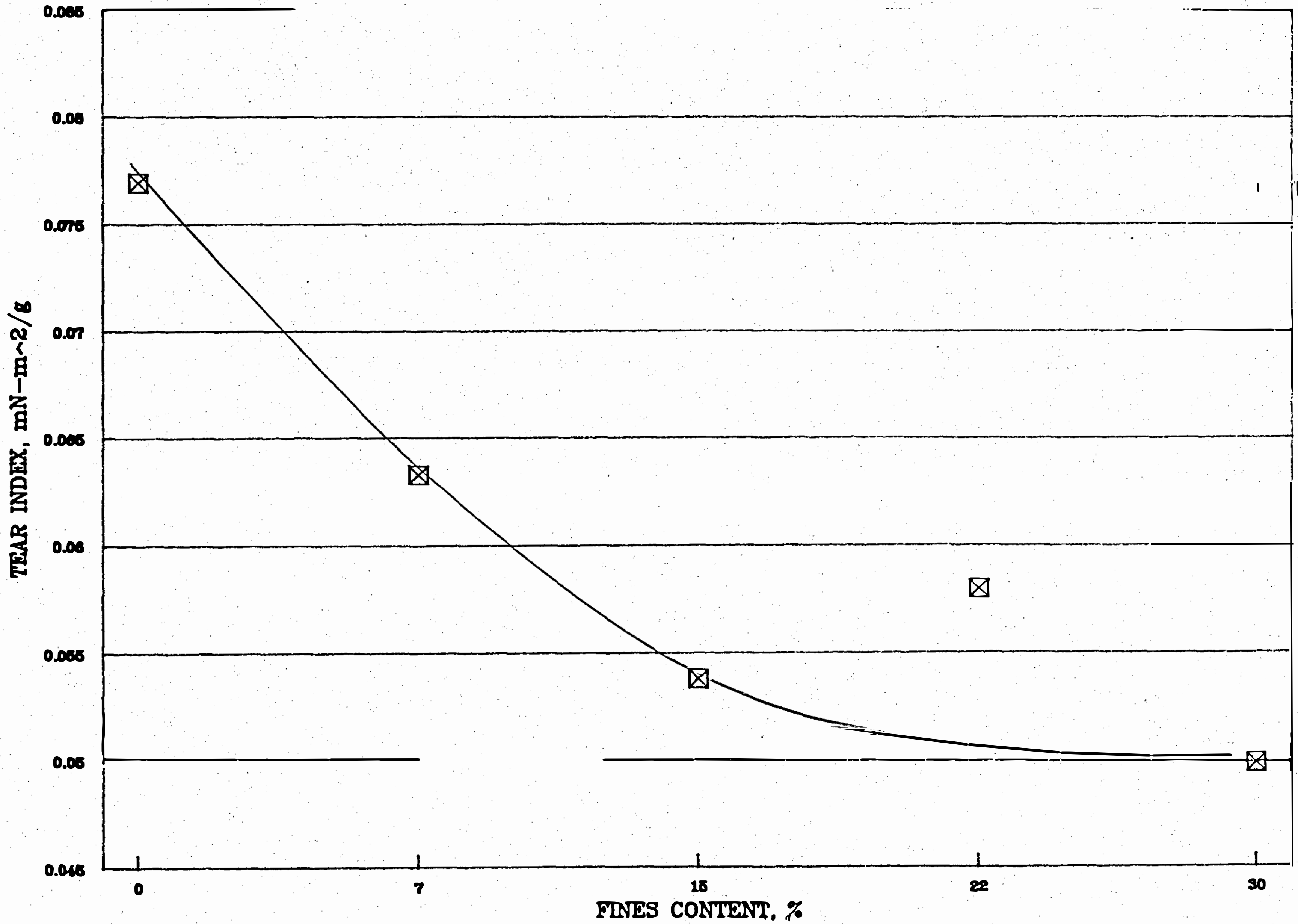


*FIGURE 30: EFFECT OF FINES CONTENT ON TEAR INDEX*

**BLEACHED KRAFT FINES**



# *FIGURE 31: EFFECT OF FINES CONTENT ON TEAR INDEX*

**UNBLEACHED KRAFT FINES**

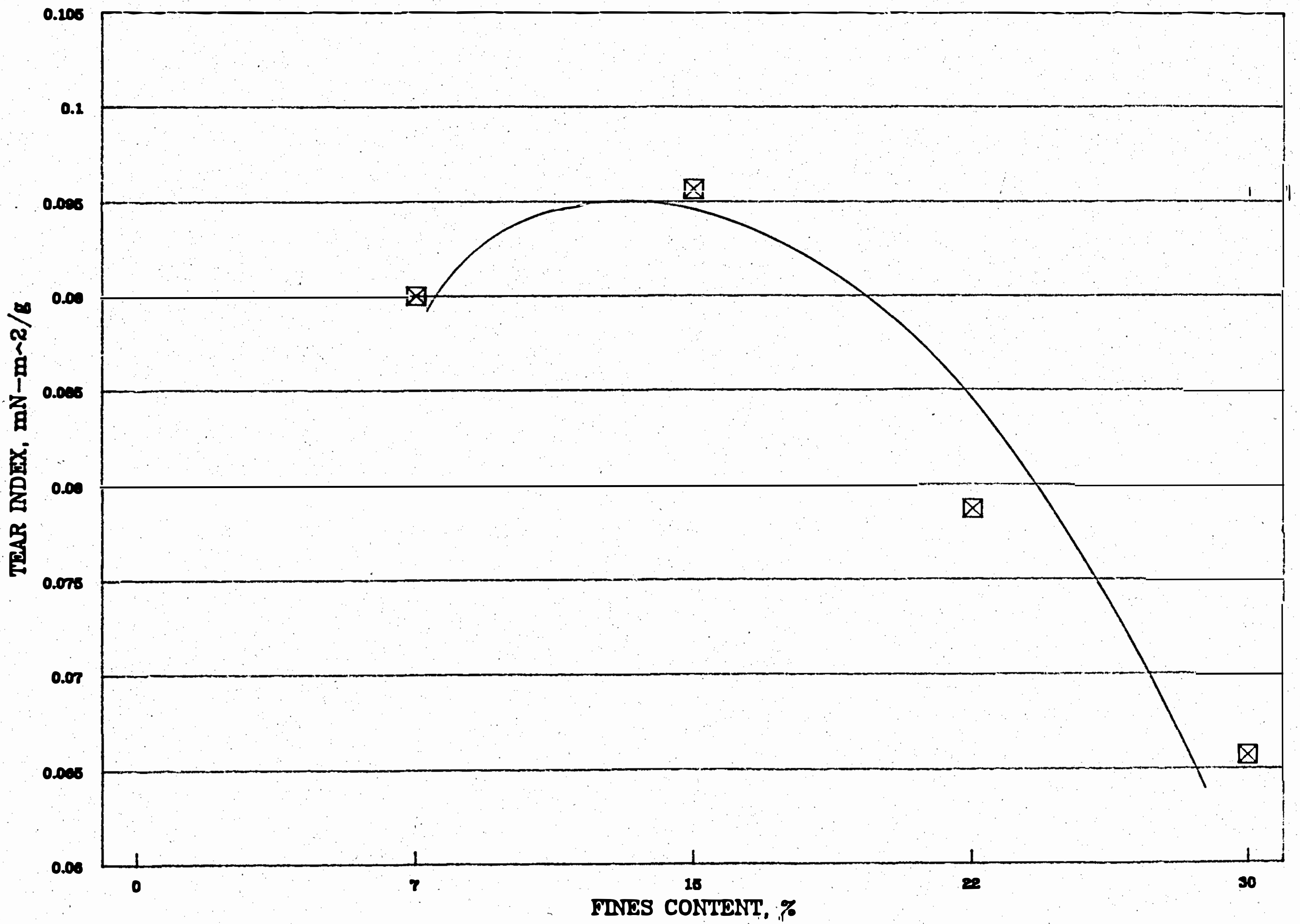
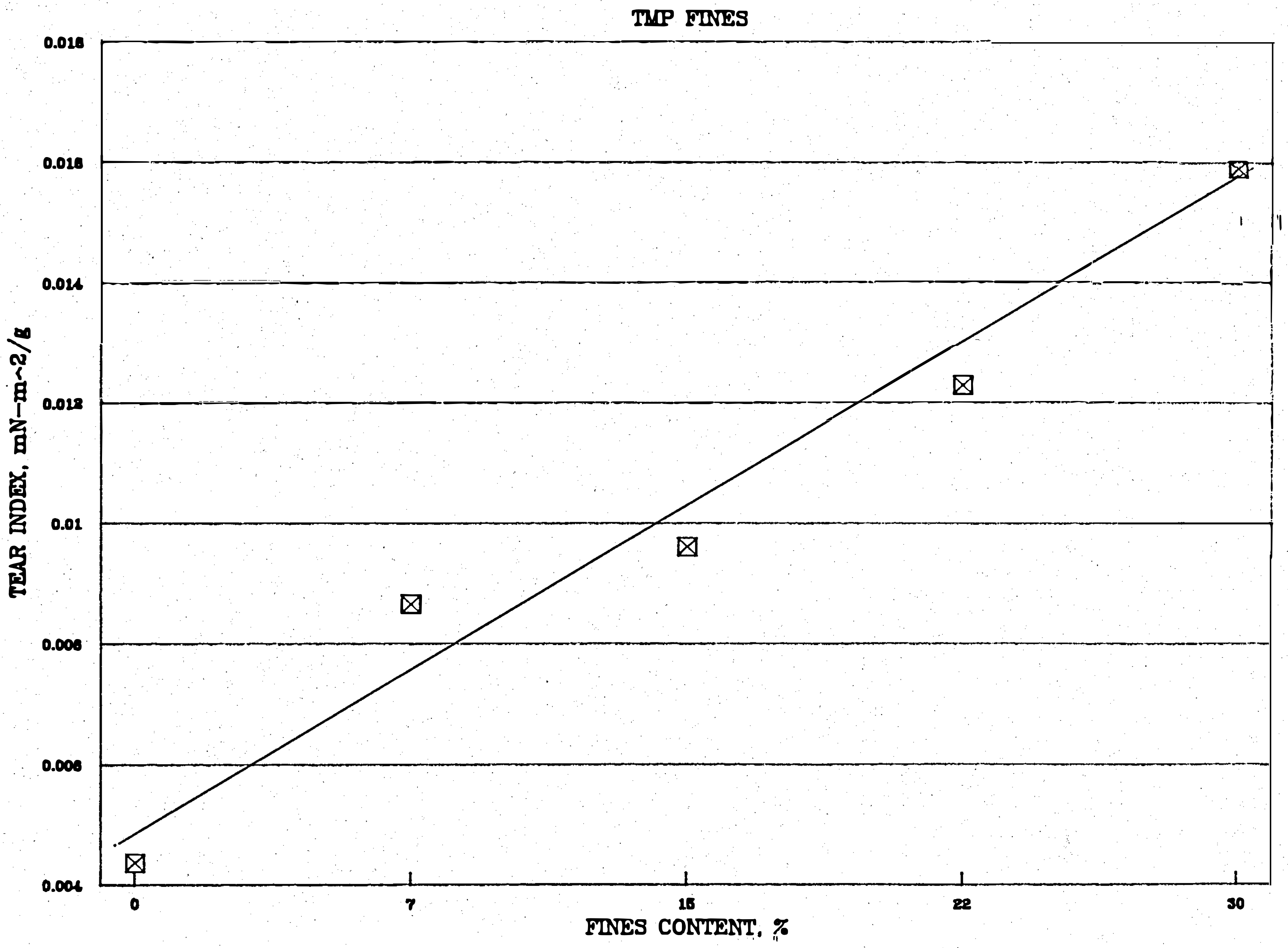


*FIGURE 32: EFFECT OF FINES CONTENT ON TEAR INDEX*



## ACTIVITY OF FINES

**Figures 33** through **38** illustrate the percent change in a given sheet property per percent change in fines level at each incremental change in fines. These figures begin on page 51. This is a way of characterizing whether the fines' effects are additive or subtractive to the sheet property development as fines levels increase. This is also a way of normalizing each type of fines' impact on their respective sheets so that the three different types of fines can be compared on the same basis. This basis of comparison will be referred to as the "activity" of the fines.

### Density

**Figure 33** shows the relative activities for the fines' impact on sheet density. The addition of fines has the biggest impact on the TMP sheets, as can be seen in the top line of the graph. This may be explained by the fact that the TMP sheet had a very low density to start with, so any additions of fines were very effective. For each incremental change in fines level, the unbleached kraft fines showed quickly improving activity, as evidenced by the slope of the unbleached line on the graph. The bleached kraft fines showed the overall lowest activity. This could be explained by the sheets' high density to start, thus any incremental increases in fines would contribute little to increasing the density any further.

Opacity

**Figure 34** illustrates the activity of each type of fines in affecting opacity. The TMP fines show the overall greatest activity, first increasing then decreasing as fines levels increase. The bleached kraft fines show an increasing activity for reducing opacity at increasing fines levels, indicating an additive type of effect. According to the points on the graph, the activity may be tapering off in the 22 to 30% fines level increase, indicating the possibility of a maximum change that may be achieved per fines addition. The unbleached kraft fines showed a low activity, with the activity decreasing slightly at higher addition levels. This may be because the sheet is so dark, with many color compounds already present to absorb light. With this, there would be little that the fines could do to affect opacity.

Brightness

**Figure 35** shows the activity of bleached kraft and TMP fines as related to sheet brightness. As can be seen, increasing the level of bleached kraft fines has little effect on the activity of the fines in reducing brightness. For the TMP fines, a decrease in activity is seen in the 7 to 15% fines level increase. This corresponds to the increase in brightness seen in **Figure 24**. However, after this point, the activity of the fines increases dramatically, corresponding to the decrease in sheet

brightness. This may be the point at which the decreased scattering coefficient combined with the color of the fines really comes into play in reducing the brightness.

Tensile Index

**Figure 36** illustrates the activity of fines in the development of tensile index. The TMP shows the greatest activity overall, but decreasing at the higher fines levels. This may be explained by the fines' contribution to bonding at the lower levels of addition, yielding large increases in tensile strength. As fines levels continue to increase, at the expense of replacing long fibers with short fines, opposing forces are created in the development of tensile strength. The bleached and unbleached kraft fines show far less activity, with decreasing activity at the higher fines levels. This may be because the sheets already possessed considerable strength without the fines. The decreasing activity may again be explained by the fact that while increasing levels of the short fines, which contribute to bonding in the sheet, the longer fiber fraction in the sheet is subsequently being decreased.

Burst Index

In **Figure 37**, the activity of bleached and unbleached kraft fines can be seen with regard to burst index. The bleached kraft fines show a dramatic decrease in activity as fines level

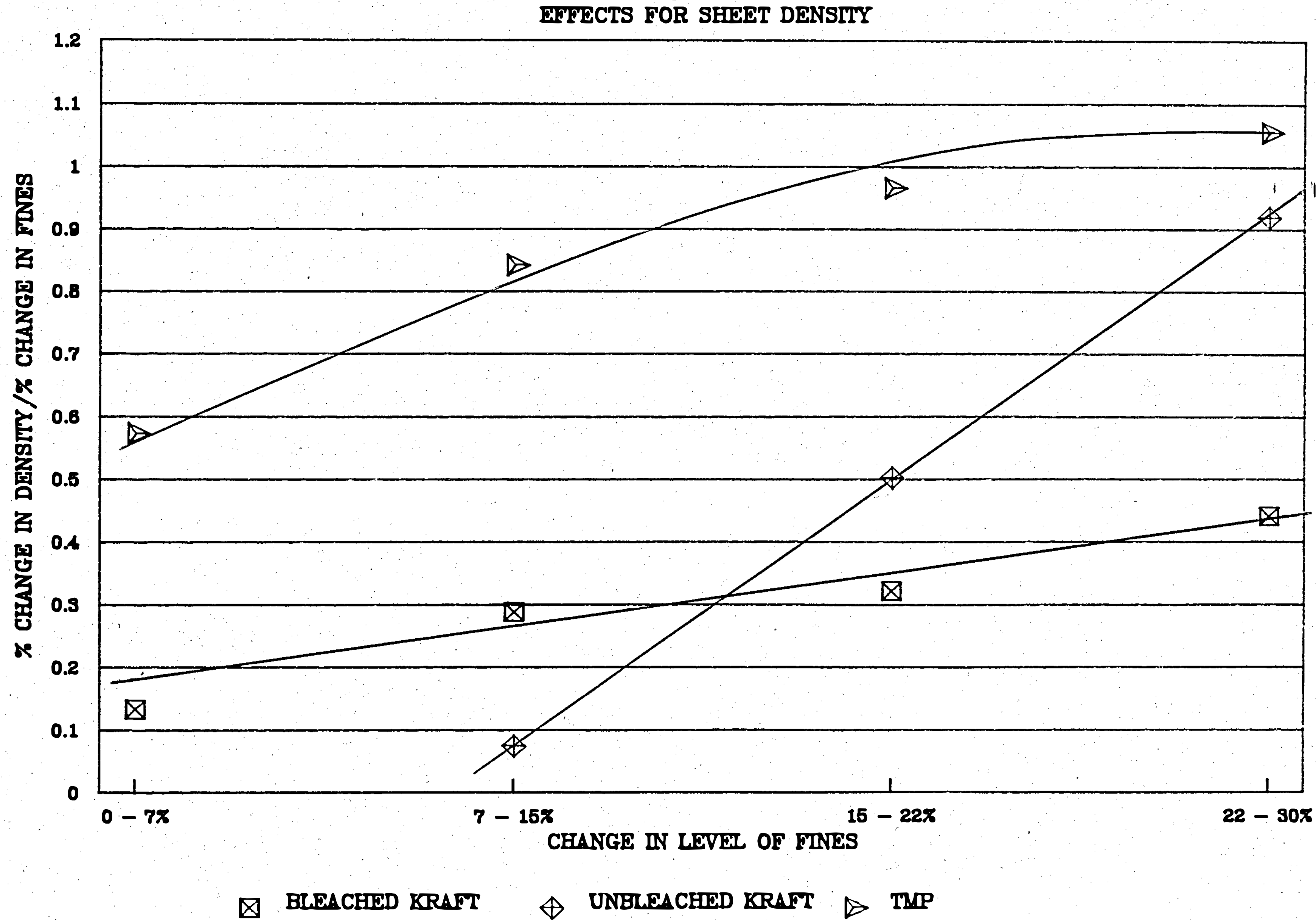
increases. This is also evident in **Figure 28**. At the higher levels of fines, the addition of extra fines has little effect on the burst index. Actually, a decrease in shown. At this point a maximum optimum level of fines may have been reached. It may be at this point where the improved bonding can no longer make up for the decreasing percentage of the pulp that is longer fibered. The unbleached fines showed an overall higher activity than the bleached fines. The activity decreased only slightly with increasing levels of fines. This may tend to indicate that further gains in burst index may be seen with fines levels higher than 30%.

Tear Index

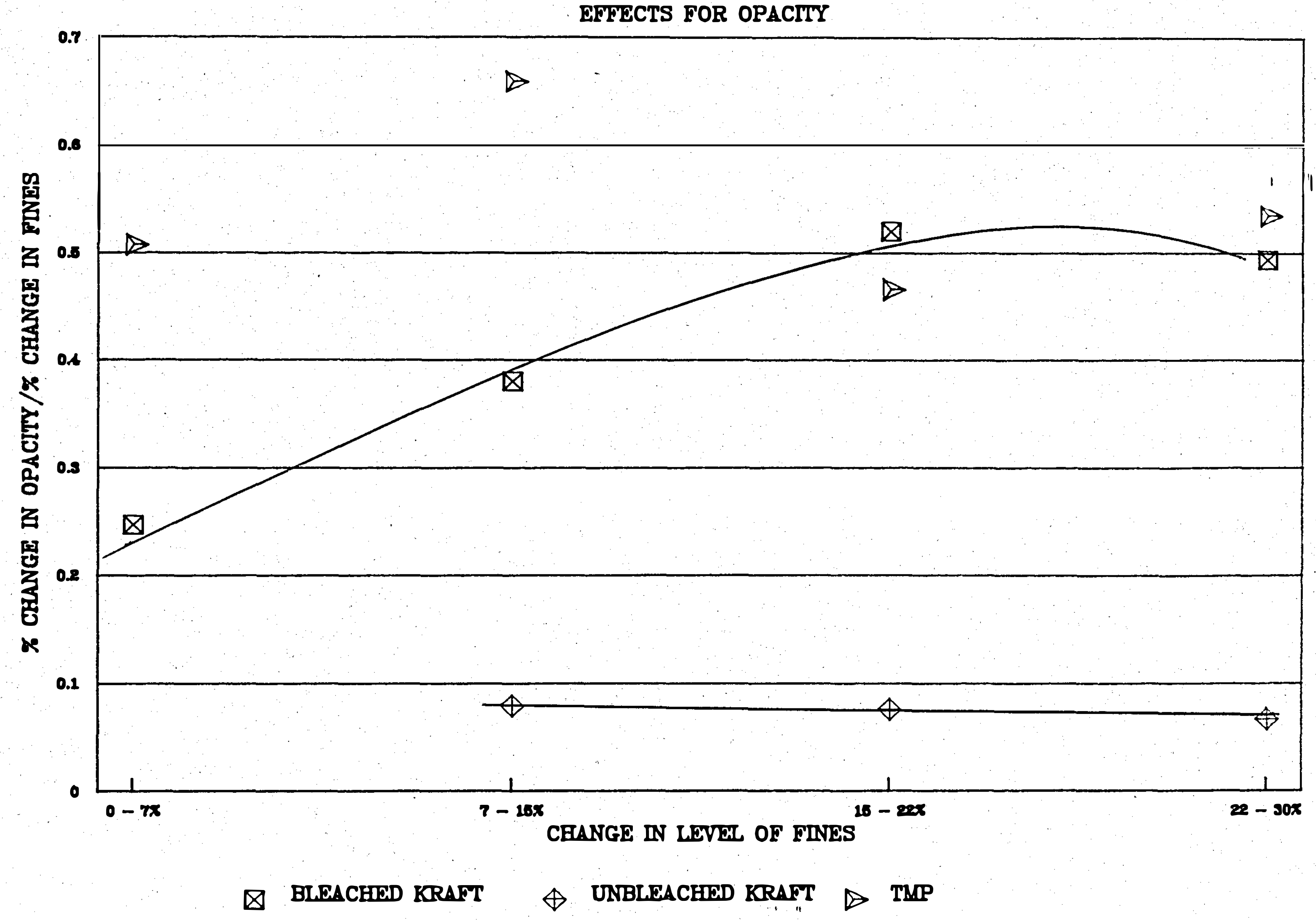
**Figure 38** illustrates the activity of fines in the development of tear index. The TMP shows the overall highest activity, but decreases as fines level increases. The fact that the TMP fines are the most active may be explained in terms of the relative strength of the sheet as compared to the other two types of pulps. As the sheet is so weak to begin with, the addition of fines may help to distribute the forces and increase tear. Within the range of fines levels evaluated, the replacement of longer fibers with fines has not yet had an effect on the tear index. The bleached kraft fines showed very little activity, increasing slightly at higher levels of addition. This activity contributes to the decrease in tear strength. As

bonding in the sheet increases, more long fibers are allowed to break, which requires less work than pulling them out of the fiber network. The increasing activity shows that at upper levels the fines are playing more of a role in decreasing sheet strength than at the lower levels. This could again be the result of the increased bonding contributed by the fines. This condition may allow for the development of other properties requiring high fines loading without significantly reducing tear. The unbleached fines also show increasing activity in reducing tear strength. This shows that as fines levels increase, the fines are contributing more to the loss of tear index, again due to the increased bonding in the sheet allowing the long fibers to break.

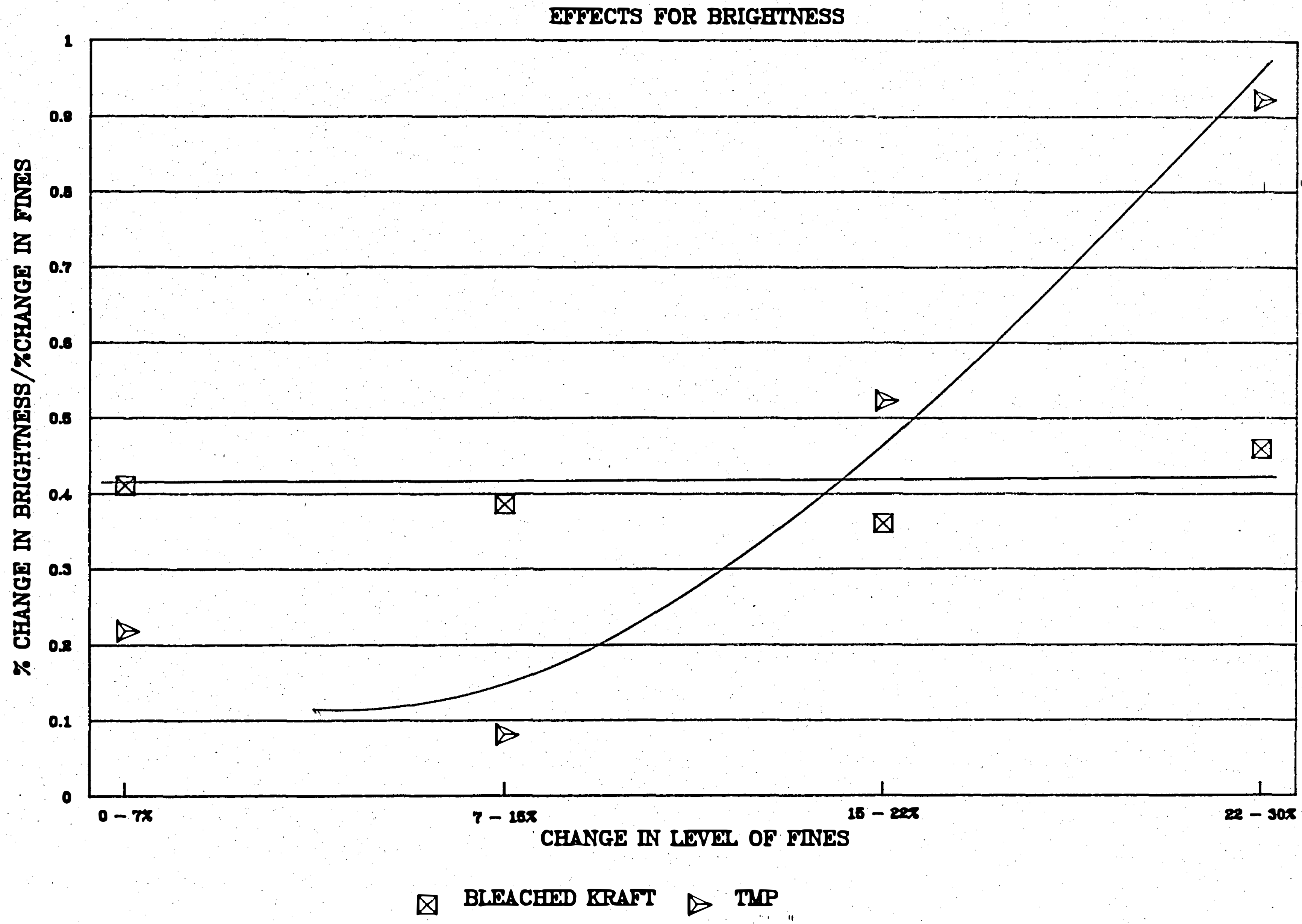
# FIGURE 33: ACTIVITY OF FINES



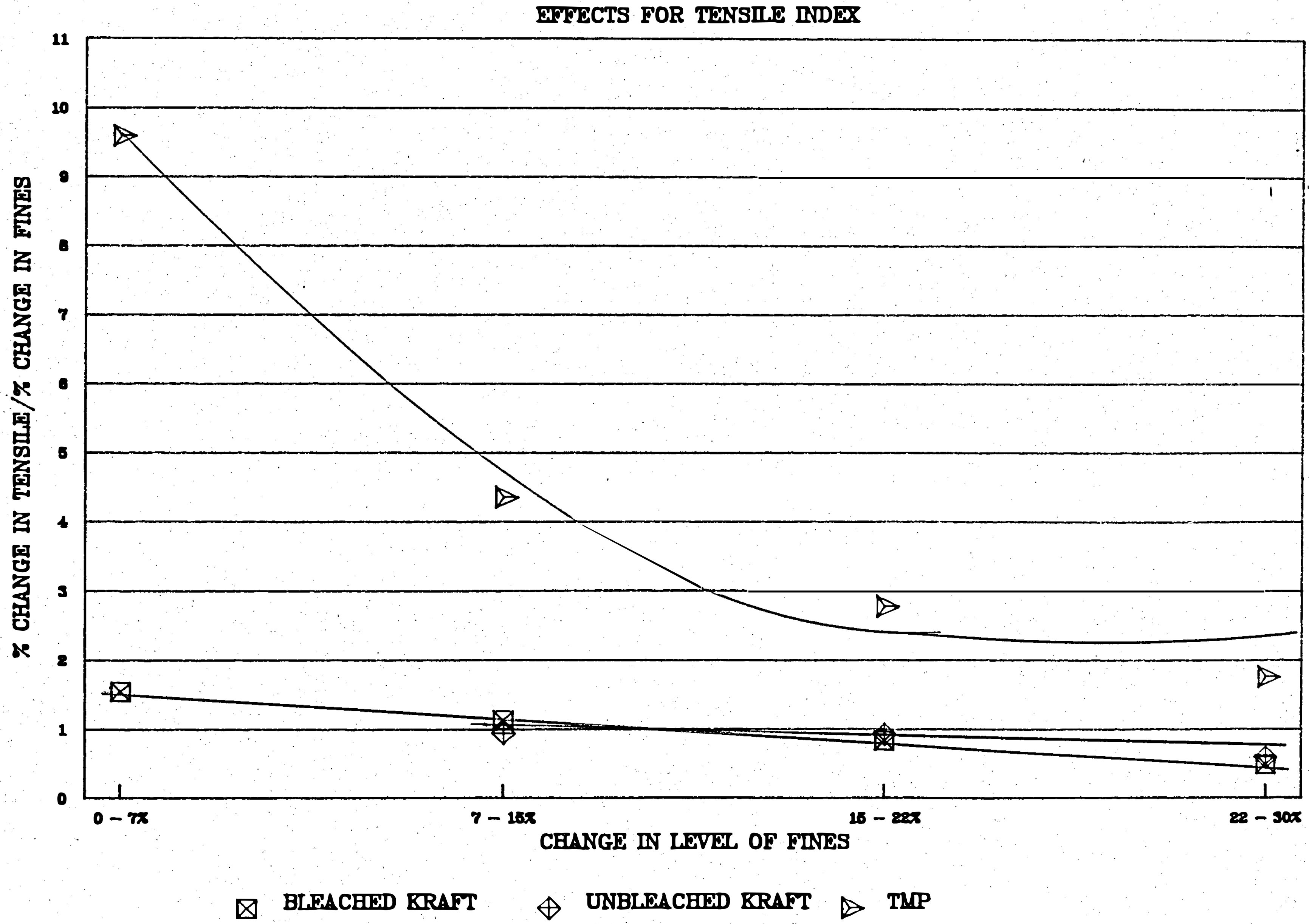
# FIGURE 34: ACTIVITY OF FINES



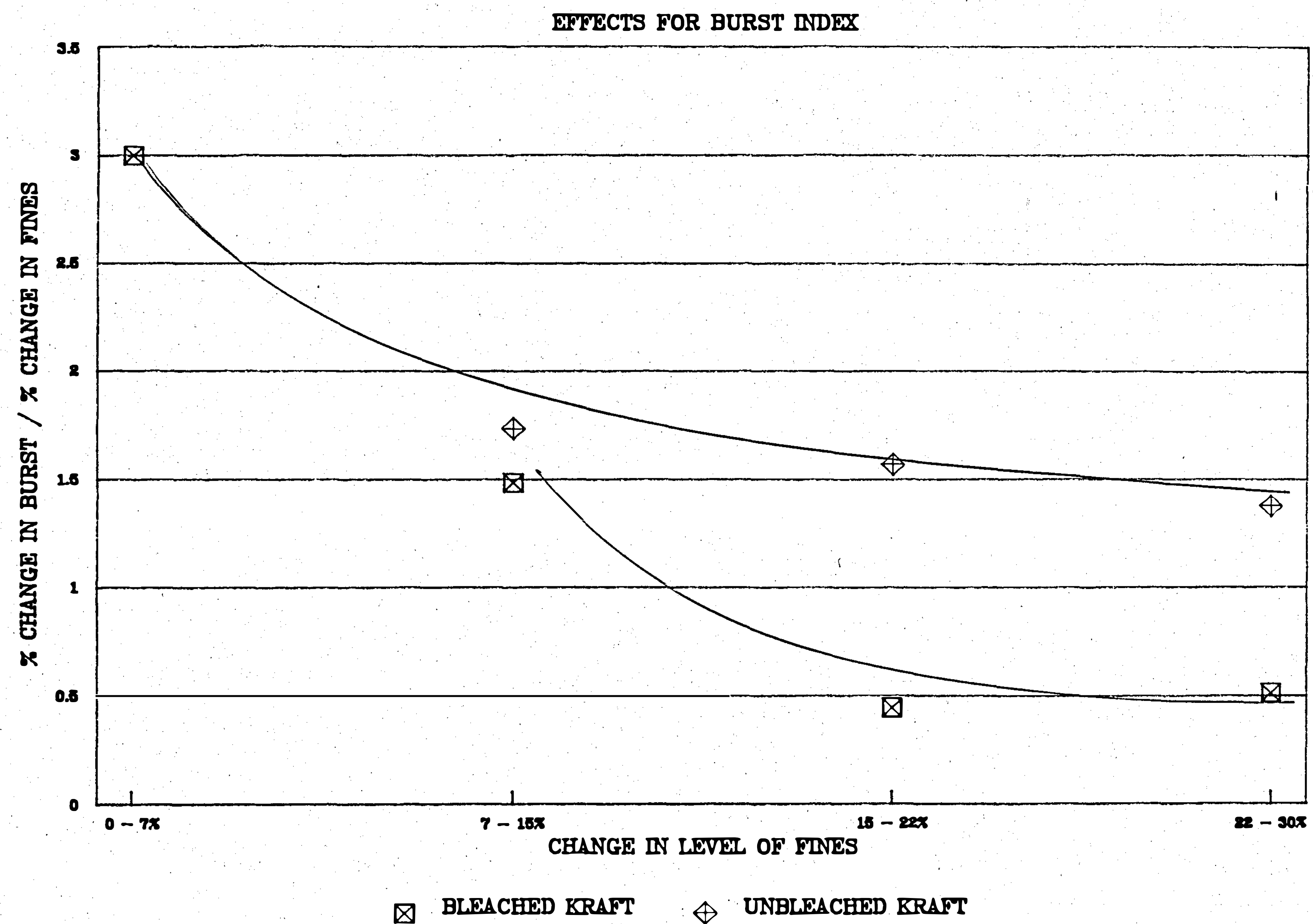
# FIGURE 35: ACTIVITY OF FINES



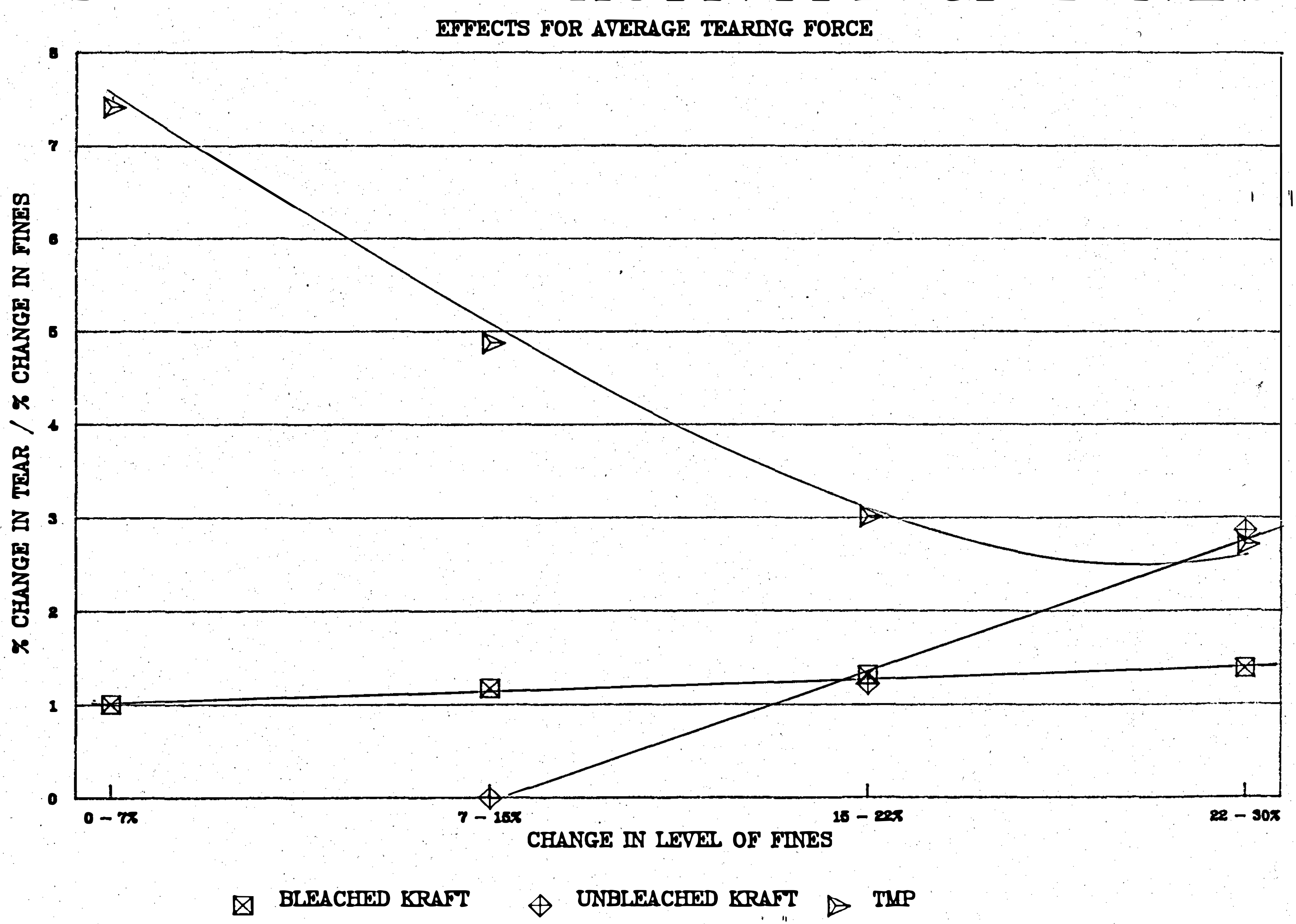
# FIGURE 36: ACTIVITY OF FINES



# FIGURE 37: ACTIVITY OF FINES



# FIGURE 38: ACTIVITY OF FINES



# SUMMARY OF RESULTS

## BLEACHED KRAFT FINES

### Properties of Bleached Kraft Fines

Photomicrographs taken of bleached kraft fines showed them to be fibrillar in nature, with a tendency to flocculate into bundles. Kajaani fiber length analysis showed that over 90% of the fines were less than 0.22 mm in length, while 42% of the material was less than 0.07 mm in length. As expected, the bleached kraft fines exhibited the highest centrifugal water retention values, holding nearly 900 grams of water per 100 grams of oven-dry fines. In drainability tests, the bleached kraft fines needed 8.67 seconds to drain 6950 ml of water, as opposed to 163.4 seconds for the unbleached kraft fines. It is believed that this is affected not only by the fines' affinity for water, but also the shapes of the fines particles. In tests to determine the compressibility of the fines, the bleached kraft fines were expected to be the most compressible. However, the data did not show this. The unbleached kraft fines were found to be more compressible. The validity of this result is questioned as it is believed that the same affects that were seen in the drainability tests may have been in play here.

### Effects of Bleached Kraft Fines on Sheet Properties

Bleached kraft fines increased sheet density as the level of fines in the sheet was increased. The activity of the fines

(percent change in sheet property per percent change in fines level) was found to increase as the level of fines in the sheet increased. This activity was the lowest overall of the fines evaluated. These fines were found to decrease the sheet scattering coefficients. As expected, this caused decreases in both opacity and brightness, as the ability to scatter light was lessened as fines level increased. Absorption coefficient also increased as fines level increased. Activity of the fines in reducing the opacity increased as fines level increased. There was no significant change in fines activity in reducing brightness as fines level increased.

As fines level increased, tensile index and burst index both increased. This was the expected result as bonding area increases in the sheet with increasing fines levels. The activity of the fines in developing tensile and burst strength decreased as fines level increased. This is the expected result. While bonding is increasing with fines addition, it must be remembered that longer fibers are being replaced with the short fines, which will give up some of the strength gain obtained from better bonding. Tear index decreased with increasing fines level, with the activity of the fines increasing slightly with increasing fines level. In this case, the addition of fines and the resultant increase in bonding allow more long fibers to break, as opposed to being pulled out of the sheet.

## UNBLEACHED KRAFT FINES

### Properties of Unbleached Kraft Fines

As seen in the photomicrographs, the unbleached kraft fines are a mix of flake-like primary fines material with fibrillar secondary fines. Again, over 90% of the material was less than 22 mm in length according to Kajaani fiber length analysis, with over 40% of the fines being less than 0.07 mm in length. Centrifugal water retention tests placed the unbleached kraft fines between the bleached kraft and the TMP fines, holding 650 grams of water per 100 grams of oven-dry fines. In testing to determine drainability of the fines, the unbleached kraft fines needed 163.4 seconds to drain 6950 ml of water. This was far longer than for the other types of fines and is probably due to filling of the forming screen and void filling in the mat. These fines were found to be more compressible than the bleached kraft fines. This is an unexpected result, and may possibly be explained by the filling of voids in the mat, offering greater resistance.

### Effects of Unbleached Kraft Fines on Sheet Properties

As expected, as fines were added to the sheet, density increased. Activity of the fines in increasing density increased as fines level increased. The overall affect was greater than that for the bleached kraft fines. Increasing the level of fines in the sheet caused a corresponding decrease in the scattering

coefficient of the sheets. This resulted in decreasing opacity as fines level increased. There was little change in the activity of the fines in reducing the opacity as fines level increased.

As the level of fines in the sheet was increased, tensile index and burst index increased. This again results from the better bonding in the sheet. In each case, the activity of the fines decreased as fines level in the sheet increased due to the opposing forces of increased bonding and the replacement of longer fibers. Tear index increased slightly between 7 and 15% fines addition, then fell off at higher levels. The activity of the fines increased steadily with fines addition.

## TMP FINES

### Properties of TMP Fines

Photomicrographs showed the TMP fines to be mainly flake-like and chunky in nature, with very little fibrillar material present. From the Kajaani fiber length analysis, 90% of the fines were found to be less than 0.22 mm in length, with 38% less than 0.07 mm in length. As expected, the TMP fines had the lowest affinity for water, as evidenced in the centrifugal water retention testing. These fines held 480 grams of water per 100 grams of oven-dry fines. In agreement with this result was the result from the drainability test. The TMP fines drained the fastest as a result of their low affinity for water and bulky,

chunk-like nature. In studying results from the compressibility test, statistical analysis of difference in drainage times between 10 and 15 inches of water vacuum showed that there was no difference between the two levels. When assuming that there is a difference between the filtration resistance of the uncompressed and the compressed mat, the TMP fines seem to be the most compressible. When taking into account that there was no statistical difference between the two resistance values, the end result is that the TMP fines are virtually incompressible.

Effects of TMP Fines on Sheet Properties

As fines level in the sheet increased, the density increased, with the activity of the fines in developing density increasing also. Opacity increased as fines level in the sheet increased. This resulted even though scattering coefficient showed a general decrease. The increase in opacity may have resulted from color present in the fines. At the same time, brightness also decreased, supporting the theory that color of the fines themselves is at work to increase opacity. Absorption coefficient increased as fines level increased. The activity of the fines for decreasing brightness increased with fines addition.

Tensile index increased with increasing levels of fines in the sheet. Activity of the fines in developing tensile strength decreased as the level of fines in the sheet increased. Tear

index also increased as fines level increased, but activity of the fines in developing tear index steadily decreased.

## CONCLUSIONS

While all of the testing to characterize fines was not successful in establishing significant trends, significant characterizations were made for some of the fines properties. The method used to characterize the fines by size proved to be inadequate in developing significant trends, as all three of the fines were found to possess essentially the same size distributions according to the Kajaani fiber length analyses. Likewise, the tests for compressibility failed to demonstrate significance in characterizing the fines. Characterizations that did exhibit significant results include type (bleached, unbleached, or mechanical) and general physical nature of the fines, water retention values of the fines, and activity of the fines in affecting sheet properties.

However, it became obvious in the analysis of the data that the best method may not have been used in determining the effects that the fines had on sheet properties, when speaking in a sense of comparison of the bleached kraft to the unbleached kraft to the TMP fines. By evaluating the fines of each of the respective pulp types and then adding them back into their own respective pulps for evaluation of effects on sheet properties, another set

of variables was added into the equation; this being the interactions of the fines with pulp of its own type with regard to development of sheet properties. It is impossible to know the effects that using fines in their own respective pulp may have had, as opposed to using each of the fines types in a single, controlled pulp type. In the case of the development of density with addition of fines, it would be expected that the more hydrophilic fines (bleached and unbleached kraft as seen in WRV tests) would have greater impact on density of the sheet. This was not the case, as the TMP fines were found to have the greatest effect on sheet density, causing the greatest percentage increase (185%) in density from 0 to 30% fines and also the greatest overall activity in increasing density. Conditions in the TMP pulp itself were causing unseen and unevaluated effects on the density with fines addition. On the other hand, the development of density in the bleached and unbleached kraft fines did follow an expected trend in that the bleached kraft fines had a slightly greater effect on the development of density than did the unbleached kraft fines. In the case of tensile strength, it was again seen that the TMP fines had by far the greatest impact of all the fines, with the tensile strength increasing 200% between 0 and 30% fines. Again, these fines also had the highest overall activity in the development of tensile strength. The bleached and unbleached kraft fines followed a more predictable course, with the more fibrillar, hemicellulose and cellulose

containing bleached kraft fines showing greater development of tensile strength than the unbleached kraft fines. This, however, was not the case with burst strength, as the unbleached kraft fines showed greater strength development.

In the area of optical properties, difficulties arose in the case of the TMP fines picking up considerable color during processing operations. This in itself adds another variable to the evaluation of the fines in affecting sheet properties. Because of this, no common ground exists on which to compare the effects of the TMP fines on brightness and opacity to the other two varieties of fines. However, in the case of scattering coefficients of the sheets containing fines, it can be concluded that the more fibrillar and compressible the fines (bleached kraft versus TMP), the more impact there will be on scattering coefficient. This was seen in the 58% drop in scattering coefficient of the bleached kraft sheets as opposed to the 12.5% drop in the scattering coefficient of the TMP sheets between 0 and 30% fines addition.

More general conclusions can be made regarding the effects that each type of fines had on the properties of each of their respective sheets. Regardless of fines type, it can be concluded that increases in sheet density and increased bonding will be seen by virtue of the small size of the fines as compared to other fractions of the pulp. Decreases in scattering coefficient can also be expected, as the small size of the fines again offers

a more compact sheet with less surface area to scatter light. Because of this, losses in opacity and brightness can be expected. Results of this study tend to indicate that fines containing lower levels of lignin and possessing a more fibrillar, water-holding type structure could be expected to result in more dramatic losses in scattering coefficient in the sheet.

In a general sense, any fines addition will give tensile and burst strength increases up to some point of fines addition. After this point, the strength increases afforded by better bonding will no longer be capable of offsetting the increasing replacement of longer fibers with the shorter fines, at which strength losses can be expected. Results of this study were unable to confirm relationships between specific properties of the fines and their role in development of strength properties.

## RECOMMENDATIONS FOR FURTHER STUDY

Because of the aforementioned problems associated with using the fines in each of their own original pulp sources, it is suggested that the effects that various fines may have on sheet properties be determined by using a single pulp source into which the various fines could added. This would eliminate the interactions that exist between fines and their original pulp source, giving common ground on which to compare the roles that various types of fines play in developing sheet properties.

Another interesting study may result from studying various mixes of softwood and hardwood fines in a sheet. In the paper industry today, nearly all paper is made using both hardwood and softwood. This could possibly result in information that is more readily applicable to papermaking today.

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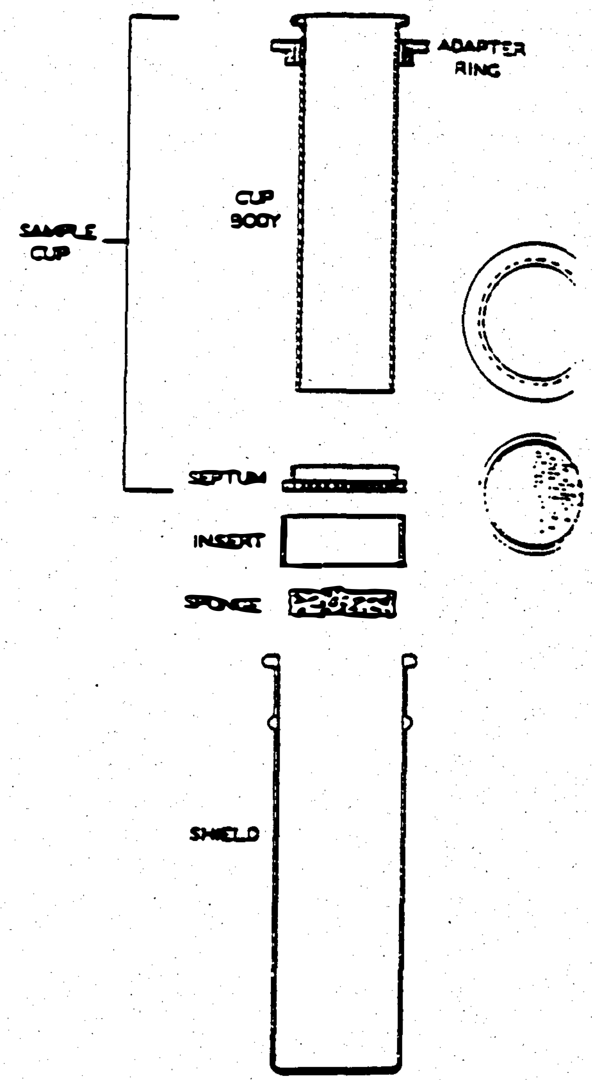
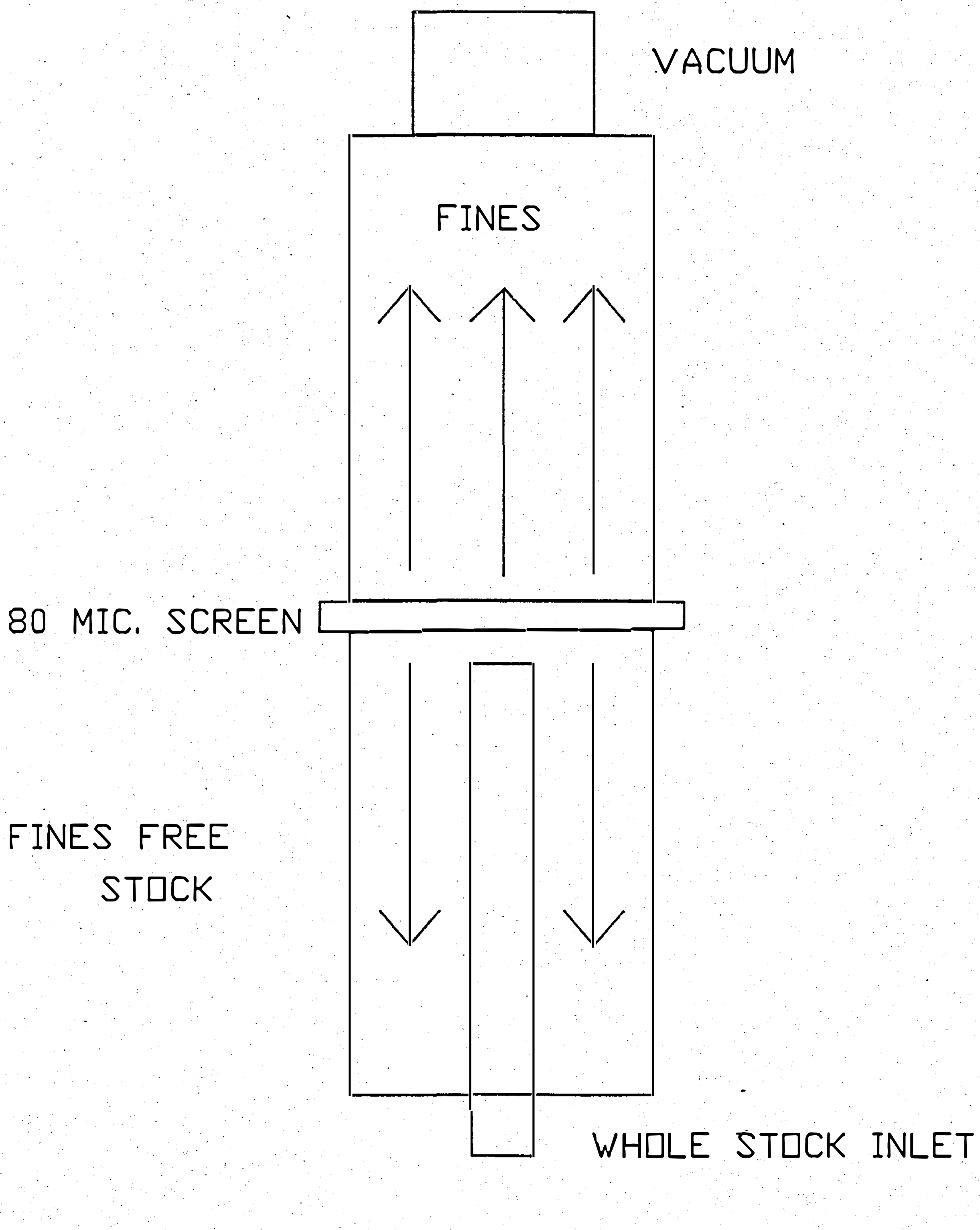
APPENDIX I: Centrifugal Cup Assembly for WRV Determination



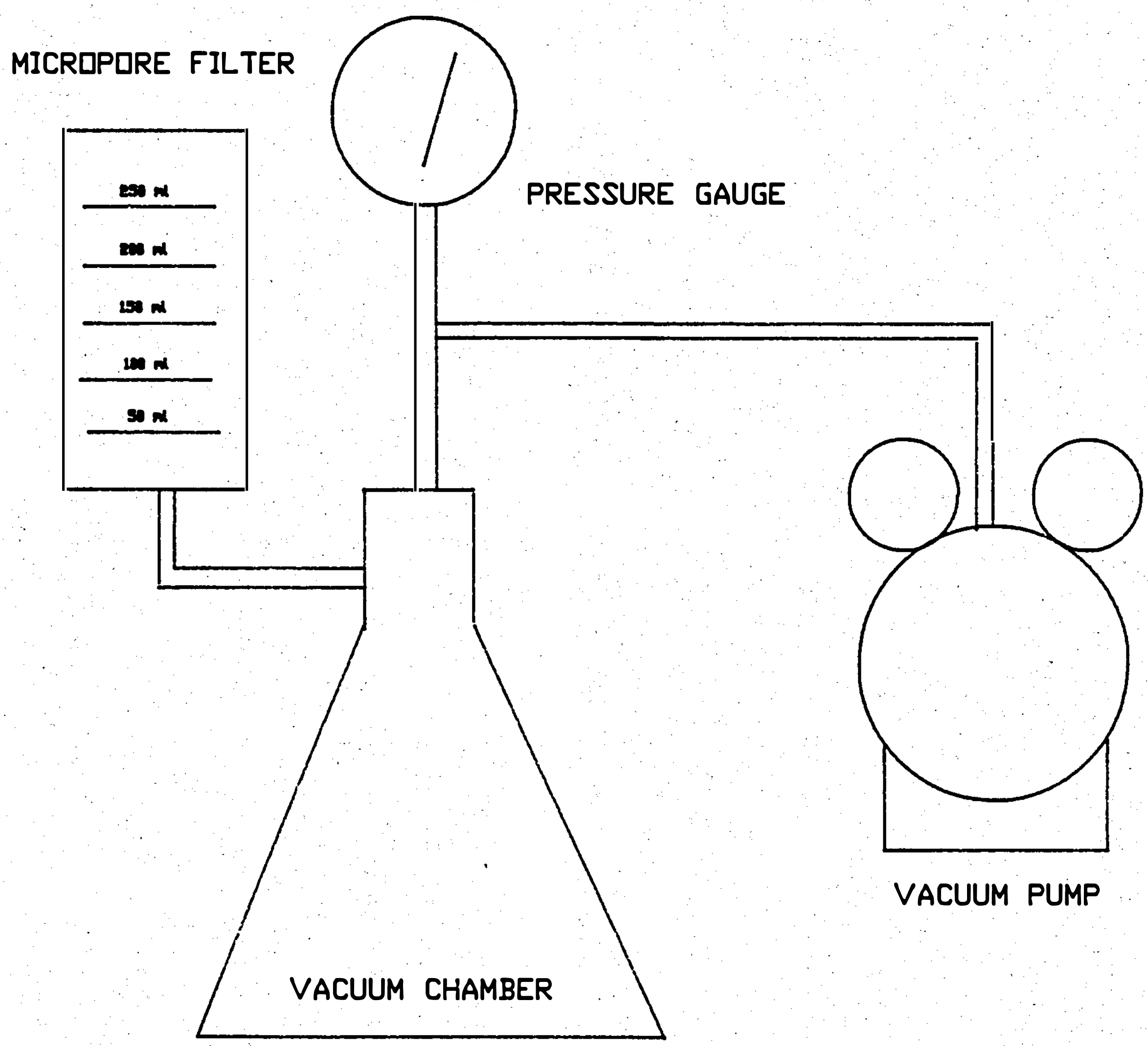

CENTRIFUGE CUP ASSEMBLY

** Illustration taken from Thode, et al. (4)

APPENDIX II: WMU Float-Wash Apparatus



APPENDIX III: Compression Filtration Resistance Apparatus



## APPENDIX IV: RESULTS OF KAJAANI FINES LENGTH DISTRIBUTION

| SIZE RANGE | BLEACHED KRAFT | TMP | UNBLEACHED |
|---|---|---|---|
| 0.00 - 0.07 mm | 42.63 | 38.52 | 40.69 |
| 0.07 - 0.14 mm | 37.38 | 40.51 | 35.62 |
| 0.15 - 0.21 mm | 14.19 | 13.98 | 15.14 |
| 0.22 - 0.28 mm | 3.54 | 3.17 | 4.96 |
| 0.29 - 0.35 mm | 1.6 | 1.53 | 2.22 |
| 0.36 - 0.42 mm | 0.43 | 0.54 | 0.6 |
| 0.43 - 0.49 mm | 0.11 | 0.27 | 0.22 |
| 0.50 - 0.56 mm | 0.02 | 0.23 | 0.09 |

** VALUES ARE PERCENT OF TOTAL SAMPLE TESTED

## APPENDIX V: CENTRIFUGAL WATER RETENTION VALUE RAW DATA

| BLEACHED KRAFT | | | UNBLEACHED KRAFT | | | TMP | | |
|---|---|---|---|---|---|---|---|---|
| WET* | DRY | WRV** | WET | DRY | WRV | WET | DRY | WRV |
| 1.35 | 0.15 | 800 | 1 | 0.13 | 669 | 1.02 | 0.18 | 467 |
| 1.51 | 0.16 | 844 | 1.07 | 0.14 | 664 | 1.1 | 0.19 | 479 |
| 1.79 | 0.17 | 953 | 1.08 | 0.14 | 671 | 1.2 | 0.2 | 500 |
| 1.65 | 0.16 | 931 | 1.14 | 0.16 | 613 | 1.05 | 0.18 | 483 |
| AVERAGES: | | | | | | | | |
| 1.58 | 0.16 | 882 | 1.07 | 0.14 | 654 | 1.09 | 0.19 | 482 |

*WEIGHTS ARE MEASURED IN GRAMS

**WRV EXPRESSED AS g. WATER/100 g. o.d. PULP

## APPENDIX VI: DRAINAGE TIME DETERMINATION IN BRITISH SHEET MOLD

(TIME TO DRAIN 6950 ml OF WATER IN SECONDS)

| | BLEACHED KRAFT | UNBLEACHED KRAFT | TMP |
|---|---|---|---|
| | 9.83 | 146.44 | 4.76 |
| | 8.46 | 154.4 | 4.92 |
| | 9.59 | 175.67 | 4.51 |
| | 8.42 | 159.61 | 5.09 |
| | 7.41 | 167.5 | 5.05 |
| | 8.09 | 163.21 | 4.47 |
| | 7.75 | 149.32 | 4.64 |
| | 9.17 | 171.2 | 4.78 |
| | 8.18 | 168.45 | 4.76 |
| | 9.78 | 178.11 | 4.7 |
| AVE: | 8.67 | 163.39 | 4.77 |

# APPENDIX VII: COMPRESSION FILTRATION RESISTANCE RAW DATA

## BLEACHED KRAFT

| | FORM TIME* | 10" HG | 15" HG | 20" HG | 28" HG |
|---|---|---|---|---|---|
| | 469.2 | 1657 | 1252 | 974.9 | 884.7 |
| | 492.8 | 1501 | 1282 | 1218.1 | 1100 |
| | 488.2 | 1661.9 | 1199 | 1167.7 | 1141 |
| | 497 | 1623.3 | 1342 | 1275 | 1113 |
| AVERAGE: | 486.8 | 1610.8 | 1268.8 | 1158.9 | 1059.7 |
| STD DEV: | 10.6 | 65.1 | 51.7 | 112.8 | 102.1 |

## TMP

| | FORM TIME | 10" HG | 15" HG | 20" HG | 28" HG |
|---|---|---|---|---|---|
| | 58 | 115 | 90 | 93.2 | 80.7 |
| | 63.1 | 199.6 | 160.25 | 135.6 | 96.4 |
| | 67.9 | 163.7 | 139.1 | 122.4 | 94 |
| | 71.7 | 114 | 103 | 93.3 | 61.7 |
| | 53.2 | 163.5 | 132.3 | | |
| AVERAGE: | 62.78 | 151.16 | 124.93 | 111.125 | 83.2 |
| STD DEV: | 6.64 | 32.69 | 25.31 | 18.47 | 13.78 |

## UNBLEACHED KRAFT

| | FORM TIME | 10" HG | 15" HG | 20" HG | 28" HG |
|---|---|---|---|---|---|
| | 663.1 | 2200.4 | 1828 | 1570.6 | 1374 |
| | 695.7 | 2156.9 | 1906.3 | 1499.3 | 1402.8 |
| | 708.3 | 2312 | 1856.4 | 1542.3 | 1396.2 |
| | 645.2 | 2297.8 | 1804.7 | 1603.1 | 1314.6 |
| AVERAGE: | 678.1 | 2241.8 | 1848.9 | 1553.8 | 1371.9 |
| STD DEV: | 25.1 | 65.2 | 37.9 | 38.1 | 34.8 |

*ALL VALUES EXPRESSED AS SECONDS TO DRAIN 50 ml

# APPENDIX VII: COMPRESSION FILTRATION RESISTANCE

Z-TEST TO DETERMINE STATISTICAL SIGNIFICANCE OF TMP RESISTANCE VALUES:

TIME TO DRAIN AT 10 INCHES VACUUM = X = 151.16 seconds
STANDARD DEVIATION = x = 32.69 seconds

TIME TO DRAIN AT 15 INCHES VACUUM = Y = 124.93 seconds
STANDARD DEVIATION = y = 25.31 seconds

IN EACH CASE, SAMPLE SIZE nX = nY = 5

Ho: X - Y = 0
Ha: X - Y not equal 0

$$Z = \frac{X - Y}{((X^2/NX)+(Y^2/NY))^{0.5}}$$

$$= \frac{151.16 - 124.93}{((1068.4/5) + (640.6/5))^{0.5}} = 1.419$$

AT A 99% CONFIDENCE INTERVAL (ALPHA = 0.01), REJECT Ho IF:

$Z <= -2.58$ OR $Z >= 2.58$

THEREFORE, Ho IS ACCEPTED AND X = Y

# APPENDIX VIII: DENSITY RAW DATA

## BLEACHED KRAFT

| PERCENT FINES | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| CALIPER, mils | 4.4 | 4.0 | 4.1 | 5.0 | 3.8 |
| | 4.2 | 4.2 | 3.9 | 4.9 | 3.8 |
| | 4.4 | 4.0 | 3.9 | 4.3 | 4.0 |
| | 4.3 | 4.1 | 4.0 | 4.0 | 3.7 |
| | 4.5 | 4.0 | 3.8 | 4.2 | 3.7 |
| | 4.4 | 4.0 | 4.0 | 4.2 | 3.7 |
| | 4.3 | 4.3 | 4.1 | 4.0 | 4.3 |
| | 4.5 | 4.5 | 4.3 | 3.8 | 3.8 |
| | 4.3 | 4.1 | 4.4 | 4.3 | 3.9 |
| | 4.0 | 4.0 | 4.4 | 4.2 | 3.8 |
| AVERAGE: | 4.3 | 4.1 | 4.1 | 4.3 | 3.9 |
| STD DEV: | 0.1 | 0.2 | 0.2 | 0.4 | 0.2 |

## UNBLEACHED KRAFT

| PERCENT FINES | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| CALIPER, mils | | 5.2 | 5.7 | 5.0 | 4.7 |
| | | 5.5 | 5.9 | 4.9 | 4.8 |
| | | 5.2 | 5.6 | 5.0 | 5.0 |
| | | 5.5 | 5.4 | 4.9 | 4.5 |
| | | 5.4 | 5.5 | 4.9 | 4.8 |
| | | 5.7 | 5.7 | 5.0 | 5.0 |
| | | 5.0 | 5.7 | 5.2 | 4.8 |
| | | 5.0 | 5.5 | 5.0 | 4.6 |
| | | 5.7 | 5.3 | 5.1 | 4.9 |
| | | 5.5 | 5.7 | 4.9 | 4.8 |
| AVERAGE: | | 5.4 | 5.6 | 5.0 | 4.8 |
| STD DEV: | | 0.2 | 0.2 | 0.1 | 0.2 |

## TMP

| PERCENT FINES | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| CALIPER, mils | 11.2 | 10.1 | 10.0 | 9.6 | 8.6 |
| | 11.1 | 10.1 | 9.6 | 10.0 | 8.4 |
| | 11.7 | 10.6 | 10.4 | 9.4 | 8.9 |
| | 10.6 | 10.6 | 11.6 | 9.4 | 8.8 |
| | 10.6 | 10.4 | 9.7 | 9.2 | 9.5 |
| | 11.0 | 10.4 | 10.7 | 10.2 | 8.4 |
| | 11.0 | 10.8 | 10.3 | 9.6 | 8.3 |
| | 11.9 | 10.8 | 9.7 | 9.9 | 9.4 |
| | 11.1 | 10.2 | 9.9 | 9.3 | 9.3 |
| | 11.0 | 10.7 | 10.1 | 9.5 | 9.2 |
| AVERAGE: | 11.1 | 10.5 | 10.2 | 9.6 | 8.9 |
| STD DEV: | 0.4 | 0.3 | 0.6 | 0.3 | 0.4 |

# APPENDIX VIII: BASIS WEIGHT TEST VALUES

## BLEACHED KRAFT

| PERCENT FINES | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| BASIS WEIGHT, g/m^2 | 58.06 | 58.06 | 56.04 | 59.07 | 58.57 |
| | 57.56 | 58.57 | 55.54 | 60.59 | 57.56 |
| | 58.06 | 58.06 | 55.54 | 58.06 | 58.06 |
| | 59.07 | 57.56 | 56.04 | 57.56 | 58.06 |
| | 56.55 | 58.57 | 55.54 | 60.59 | 57.56 |
| | 58.06 | 58.57 | 55.03 | 58.57 | 57.56 |
| | 59.58 | 57.56 | 56.55 | 60.08 | 58.57 |
| | 57.05 | 58.57 | 55.54 | 60.59 | 57.56 |
| | 57.56 | 58.06 | 56.04 | 58.57 | 57.56 |
| | 57.05 | 58.06 | 56.04 | 58.06 | 58.57 |
| AVERAGE: | 57.86 | 58.16 | 55.79 | 59.17 | 57.96 |
| STD DEV: | 0.88 | 0.38 | 0.41 | 1.12 | 0.44 |

## UNBLEACHED KRAFT

| PERCENT FINES | 7 | 15 | 22 | 30 |
|---|---|---|---|---|
| BASIS WEIGHT, g/m^2 | 57.56 | 56.55 | 57.56 | 57.05 |
| | 57.56 | 57.05 | 58.57 | 57.05 |
| | 58.06 | 58.57 | 57.56 | 57.56 |
| | 58.06 | 57.05 | 58.06 | 57.56 |
| | 58.06 | 59.07 | 58.06 | 58.06 |
| | 58.06 | 58.57 | 58.06 | 57.56 |
| | 58.06 | 57.56 | 58.06 | 58.06 |
| | 57.56 | 57.56 | 57.56 | 58.06 |
| | 58.06 | 58.06 | 58.57 | 57.05 |
| | 57.56 | 56.55 | 58.06 | 57.05 |
| AVERAGE: | 57.86 | 57.66 | 58.01 | 57.51 |
| STD DEV: | 0.25 | 0.84 | 0.35 | 0.42 |

## TMP

| PERCENT FINES | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| BASIS WEIGHT, g/m^2 | 58.06 | 56.55 | 57.05 | 57.05 | 58.57 |
| | 57.56 | 56.55 | 58.06 | 58.06 | 58.57 |
| | 57.56 | 56.55 | 56.04 | 58.06 | 58.06 |
| | 57.05 | 56.55 | 57.56 | 58.06 | 57.56 |
| | 55.54 | 57.05 | 57.56 | 58.57 | 57.56 |
| | 56.55 | 56.04 | 57.05 | 57.56 | 58.06 |
| | 56.04 | 57.05 | 58.06 | 57.56 | 58.06 |
| | 57.56 | 56.55 | 56.04 | 58.06 | 58.57 |
| | 57.56 | 56.55 | 57.56 | 58.57 | 58.06 |
| | 58.06 | 57.05 | 57.56 | 58.06 | 57.56 |
| AVERAGE: | 57.15 | 56.65 | 57.26 | 57.96 | 58.06 |
| STD DEV: | 0.81 | 0.30 | 0.68 | 0.44 | 0.39 |

# APPENDIX IX: OPACITY RAW DATA

## BLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| % OPACITY | 61.1 | 60.5 | 59.2 | 55.4 | 56.3 |
| | 64.4 | 61.1 | 61.6 | 60.6 | 50.6 |
| | 65.6 | 62 | 57 | 58.1 | 58.4 |
| | 63.4 | 60.1 | 62.7 | 58.4 | 55.9 |
| | 64.9 | 69.4 | 60.2 | 59.7 | 53.6 |
| | 64.5 | 62.3 | 59 | 60.7 | 55.8 |
| | 62.7 | 63.4 | 58.9 | 60.7 | 55.7 |
| | 63.2 | 61 | 61.2 | 56.5 | 51.9 |
| | 64.1 | 61.6 | 58.8 | 62 | 56.7 |
| | 62.9 | 61 | 58.3 | 63 | 54.8 |
| AVERAGE: | 63.7 | 62.2 | 59.7 | 59.5 | 55.0 |
| STD DEV: | 1.23 | 2.55 | 1.63 | 2.27 | 2.21 |

## TMP

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| % OPACITY | 79.2 | 79.7 | 85.2 | 91.2 | 92.2 |
| | 78 | 79 | 84.6 | 89.5 | 92.6 |
| | 77.5 | 82.1 | 83.2 | 90.7 | 92.8 |
| | 79.6 | 81.1 | 85.8 | 89.8 | 91.4 |
| | 79.9 | 81.4 | 86.1 | 91.1 | 92 |
| | 78.6 | 81.8 | 86 | 90.2 | 91.1 |
| | 78 | 83.5 | 84 | 88.9 | 92.6 |
| | 80.9 | 81.4 | 84.2 | 90.5 | 92.4 |
| | 78.5 | 83.7 | 85.5 | 89.8 | 92.5 |
| | 77.8 | 83.2 | 85.1 | 92.9 | 91.1 |
| AVERAGE: | 78.8 | 81.7 | 85.0 | 90.5 | 92.1 |
| STD DEV: | 1.03 | 1.47 | 0.90 | 1.06 | 0.61 |

## UNBLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| %OPACITY | | 95.5 | 92.2 | 92 | 92.3 |
| | | 94.3 | 92.7 | 93.4 | 92.1 |
| | | 97 | 94.6 | 94.9 | 90.3 |
| | | 94.9 | 95.2 | 94.2 | 93.9 |
| | | 94.9 | 95.5 | 92.8 | 92 |
| | | 95.2 | 95.5 | 93.9 | 93.5 |
| | | 94.4 | 92.9 | 92.9 | 96 |
| | | 95.9 | 94.9 | 92.9 | 96.6 |
| | | 94.3 | 91.7 | 92.9 | 94.1 |
| | | 96.1 | 92.4 | 93.3 | 94.9 |
| AVERAGE: | | 95.3 | 93.8 | 93.3 | 93.6 |
| STD DEV: | | 0.84 | 1.43 | 0.78 | 1.85 |

15% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.955 | 0.565 | 1.00106 | 0.04606 | 1.690 | 1.360 | 14.767 | 264.68 | 55.79 |
| 0.954 | 0.588 | 1.00111 | 0.04711 | 1.622 | 1.438 | 15.265 | 273.61 | 55.79 |
| 0.958 | 0.546 | 1.00092 | 0.04292 | 1.755 | 1.295 | 15.084 | 270.38 | 55.79 |
| 0.958 | 0.601 | 1.00092 | 0.04292 | 1.594 | 1.474 | 17.172 | 307.80 | 55.79 |
| 0.955 | 0.575 | 1.00106 | 0.04606 | 1.661 | 1.393 | 15.120 | 271.01 | 55.79 |
| 0.956 | 0.564 | 1.00101 | 0.04501 | 1.695 | 1.355 | 15.054 | 269.83 | 55.79 |
| 0.954 | 0.562 | 1.00111 | 0.04711 | 1.698 | 1.353 | 14.356 | 257.32 | 55.79 |
| 0.955 | 0.584 | 1.00106 | 0.04606 | 1.635 | 1.423 | 15.444 | 276.82 | 55.79 |
| 0.956 | 0.562 | 1.00101 | 0.04501 | 1.701 | 1.349 | 14.982 | 268.55 | 55.79 |
| 0.951 | 0.554 | 1.00126 | 0.05026 | 1.717 | 1.333 | 13.257 | 237.62 | 55.79 |
| | | | | | | | | |
| 0.955 | 0.570 | 1.00105 | 0.04585 | 1.677 | 1.377 | 15.050 | 269.76 | |
| | | | | | | STD DEV | 16.5188 | |

22% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.962 | 0.533 | 1.00075 | 0.03875 | 1.805 | 1.248 | 16.108 | 272.24 | 59.17 |
| 0.962 | 0.583 | 1.00075 | 0.03875 | 1.650 | 1.405 | 18.132 | 306.44 | 59.17 |
| 0.964 | 0.56 | 1.00067 | 0.03667 | 1.721 | 1.328 | 18.102 | 305.93 | 59.17 |
| 0.963 | 0.562 | 1.00071 | 0.03771 | 1.714 | 1.336 | 17.711 | 299.32 | 59.17 |
| 0.955 | 0.57 | 1.00106 | 0.04606 | 1.675 | 1.377 | 14.942 | 252.53 | 59.17 |
| 0.962 | 0.584 | 1.00075 | 0.03875 | 1.647 | 1.409 | 18.174 | 307.16 | 59.17 |
| 0.961 | 0.583 | 1.00079 | 0.03979 | 1.648 | 1.407 | 17.683 | 298.85 | 59.17 |
| 0.956 | 0.54 | 1.00101 | 0.04501 | 1.770 | 1.280 | 14.217 | 240.27 | 59.17 |
| 0.951 | 0.59 | 1.00126 | 0.05026 | 1.612 | 1.451 | 14.437 | 244.00 | 59.17 |
| 0.953 | 0.6 | 1.00116 | 0.04816 | 1.588 | 1.481 | 15.381 | 259.95 | 59.17 |
| | | | | | | | | |
| 0.959 | 0.571 | 1.00089 | 0.04199 | 1.683 | 1.372 | 16.489 | 278.67 | |
| | | | | | | STD DEV | 26.2887 | |

30% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.954 | 0.537 | 1.00111 | 0.04711 | 1.777 | 1.274 | 13.523 | 233.32 | 57.96 |
| 0.961 | 0.486 | 1.00079 | 0.03979 | 1.977 | 1.114 | 13.997 | 241.50 | 57.96 |
| 0.944 | 0.551 | 1.00166 | 0.05766 | 1.713 | 1.336 | 11.586 | 199.89 | 57.96 |
| 0.95 | 0.531 | 1.00132 | 0.05132 | 1.789 | 1.263 | 12.302 | 212.25 | 57.96 |
| 0.956 | 0.512 | 1.00101 | 0.04501 | 1.867 | 1.196 | 13.283 | 229.18 | 57.96 |
| 0.95 | 0.53 | 1.00132 | 0.05132 | 1.792 | 1.260 | 12.272 | 211.74 | 57.96 |
| 0.963 | 0.536 | 1.00071 | 0.03771 | 1.797 | 1.256 | 16.650 | 287.27 | 57.96 |
| 0.966 | 0.501 | 1.0006 | 0.0346 | 1.928 | 1.149 | 16.604 | 286.47 | 57.96 |
| 0.96 | 0.544 | 1.00083 | 0.04083 | 1.765 | 1.285 | 15.737 | 271.52 | 57.96 |
| 0.955 | 0.523 | 1.00106 | 0.04606 | 1.826 | 1.230 | 13.352 | 230.37 | 57.96 |
| | | | | | | | | |
| 0.956 | 0.525 | 1.00104 | 0.04514 | 1.823 | 1.236 | 13.931 | 240.35 | |
| | | | | | | STD DEV | 29.6984 | |

# APPENDIX X : SCATTERING COEFFICIENTS FOR UNBLEACHED KRAFT SHEETS

7% FINES

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.373 | 0.343 | 1.52698 | 1.15398 | 1.087 | 3.172 | 1.375 | 23.76 | 57.86 |
| 0.379 | 0.354 | 1.50876 | 1.12976 | 1.071 | 3.378 | 1.495 | 25.84 | 57.86 |
| 0.335 | 0.318 | 1.66004 | 1.32504 | 1.053 | 3.648 | 1.377 | 23.79 | 57.86 |
| 0.342 | 0.322 | 1.63299 | 1.29099 | 1.062 | 3.503 | 1.357 | 23.45 | 57.86 |
| 0.349 | 0.324 | 1.60716 | 1.25816 | 1.077 | 3.293 | 1.309 | 22.62 | 57.86 |
| 0.343 | 0.322 | 1.62923 | 1.28623 | 1.065 | 3.455 | 1.343 | 23.21 | 57.86 |
| 0.34 | 0.316 | 1.64059 | 1.30059 | 1.076 | 3.308 | 1.272 | 21.98 | 57.86 |
| 0.338 | 0.314 | 1.64829 | 1.31029 | 1.076 | 3.302 | 1.260 | 21.78 | 57.86 |
| 0.339 | 0.315 | 1.64443 | 1.30543 | 1.076 | 3.305 | 1.266 | 21.88 | 57.86 |
| 0.343 | 0.32 | 1.62923 | 1.28623 | 1.072 | 3.361 | 1.307 | 22.58 | 57.86 |
| | | | | | | | | |
| 0.348 | 0.325 | 1.61277 | 1.26467 | 1.072 | 3.373 | 1.336 | 23.09 | |
| | | | | | | STD DEV | 1.16407 | |

15% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.387 | 0.357 | 1.48549 | 1.09849 | 1.084 | 3.211 | 1.461 | 25.35 | 57.66 |
| 0.382 | 0.358 | 1.4999 | 1.1179 | 1.067 | 3.429 | 1.533 | 26.60 | 57.66 |
| 0.371 | 0.351 | 1.53321 | 1.16221 | 1.057 | 3.586 | 1.543 | 26.76 | 57.66 |
| 0.374 | 0.356 | 1.5239 | 1.1499 | 1.051 | 3.703 | 1.610 | 27.92 | 57.66 |
| 0.357 | 0.341 | 1.57906 | 1.22206 | 1.047 | 3.776 | 1.545 | 26.79 | 57.66 |
| 0.378 | 0.361 | 1.51175 | 1.13375 | 1.047 | 3.772 | 1.664 | 28.85 | 57.66 |
| 0.382 | 0.355 | 1.4999 | 1.1179 | 1.076 | 3.307 | 1.479 | 25.65 | 57.66 |
| 0.375 | 0.356 | 1.52083 | 1.14583 | 1.053 | 3.650 | 1.593 | 27.62 | 57.66 |
| 0.385 | 0.353 | 1.4912 | 1.1062 | 1.091 | 3.138 | 1.418 | 24.60 | 57.66 |
| 0.383 | 0.354 | 1.49698 | 1.11398 | 1.082 | 3.235 | 1.452 | 25.18 | 57.66 |
| | | | | | | | | |
| 0.377 | 0.354 | 1.51422 | 1.13682 | 1.065 | 3.481 | 1.530 | 26.53 | |
| | | | | | | STD DEV | 1.27873 | |

22% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.373 | 0.343 | 1.52698 | 1.15398 | 1.087 | 3.172 | 1.375 | 23.70 | 58.01 |
| 0.379 | 0.354 | 1.50876 | 1.12976 | 1.071 | 3.378 | 1.495 | 25.77 | 58.01 |
| 0.335 | 0.318 | 1.66004 | 1.32504 | 1.053 | 3.648 | 1.377 | 23.73 | 58.01 |
| 0.342 | 0.322 | 1.63299 | 1.29099 | 1.062 | 3.503 | 1.357 | 23.38 | 58.01 |
| 0.349 | 0.324 | 1.60716 | 1.25816 | 1.077 | 3.293 | 1.309 | 22.56 | 58.01 |
| 0.343 | 0.322 | 1.62923 | 1.28623 | 1.065 | 3.455 | 1.343 | 23.15 | 58.01 |
| 0.34 | 0.316 | 1.64059 | 1.30059 | 1.076 | 3.308 | 1.272 | 21.92 | 58.01 |
| 0.338 | 0.314 | 1.64829 | 1.31029 | 1.076 | 3.302 | 1.260 | 21.72 | 58.01 |
| 0.339 | 0.315 | 1.64443 | 1.30543 | 1.076 | 3.305 | 1.266 | 21.82 | 58.01 |
| 0.343 | 0.32 | 1.62923 | 1.28623 | 1.072 | 3.361 | 1.307 | 22.52 | 58.01 |
| | | | | | | | | |
| 0.348 | 0.325 | 1.61277 | 1.26467 | 1.072 | 3.373 | 1.336 | 23.03 | |
| | | | | | | STD DEV | 1.16106 | |

30% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.352 | 0.325 | 1.59645 | 1.24445 | 1.083 | 3.222 | 1.294 | 22.51 | 57.51 |
| 0.355 | 0.327 | 1.58595 | 1.23095 | 1.086 | 3.193 | 1.297 | 22.55 | 57.51 |
| 0.339 | 0.306 | 1.64443 | 1.30543 | 1.108 | 2.973 | 1.139 | 19.80 | 57.51 |
| 0.345 | 0.324 | 1.62178 | 1.27678 | 1.065 | 3.461 | 1.355 | 23.57 | 57.51 |
| 0.35 | 0.322 | 1.60357 | 1.25357 | 1.087 | 3.178 | 1.268 | 22.04 | 57.51 |
| 0.325 | 0.304 | 1.70096 | 1.37596 | 1.069 | 3.400 | 1.235 | 21.48 | 57.51 |
| 0.347 | 0.333 | 1.61442 | 1.26742 | 1.042 | 3.883 | 1.532 | 26.64 | 57.51 |
| 0.354 | 0.342 | 1.58943 | 1.23543 | 1.035 | 4.060 | 1.643 | 28.57 | 57.51 |
| 0.353 | 0.332 | 1.59293 | 1.23993 | 1.063 | 3.485 | 1.405 | 24.44 | 57.51 |
| 0.352 | 0.334 | 1.59645 | 1.24445 | 1.054 | 3.641 | 1.463 | 25.43 | 57.51 |
| | | | | | | | | |
| 0.347 | 0.325 | 1.61464 | 1.26744 | 1.069 | 3.450 | 1.363 | 23.70 | |
| | | | | | | STD DEV | 2.48168 | |

# APPENDIX X: SCATTERING COEFFICIENTS FOR TMP SHEETS

## 0% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.773 | 0.612 | 1.03333 | 0.26033 | 1.263 | 2.152 | 4.133 | 72.32 | 57.15 |
| 0.774 | 0.604 | 1.03299 | 0.25899 | 1.281 | 2.093 | 4.040 | 70.69 | 57.15 |
| 0.774 | 0.6 | 1.03299 | 0.25899 | 1.290 | 2.066 | 3.989 | 69.80 | 57.15 |
| 0.773 | 0.615 | 1.03333 | 0.26033 | 1.257 | 2.173 | 4.174 | 73.03 | 57.15 |
| 0.758 | 0.606 | 1.03863 | 0.28063 | 1.251 | 2.194 | 3.910 | 68.41 | 57.15 |
| 0.771 | 0.606 | 1.03401 | 0.26301 | 1.272 | 2.122 | 4.034 | 70.58 | 57.15 |
| 0.769 | 0.6 | 1.0347 | 0.2657 | 1.282 | 2.092 | 3.937 | 68.88 | 57.15 |
| 0.758 | 0.613 | 1.03863 | 0.28063 | 1.237 | 2.247 | 4.003 | 70.04 | 57.15 |
| 0.769 | 0.603 | 1.0347 | 0.2657 | 1.275 | 2.112 | 3.975 | 69.55 | 57.15 |
| 0.772 | 0.601 | 1.03367 | 0.26167 | 1.285 | 2.083 | 3.980 | 69.65 | 57.15 |
| | | | | | | | | |
| 0.769 | 0.606 | 1.0347 | 0.2656 | 1.269 | 2.133 | 4.017 | 70.29 | |
| | | | | | | STD DEV | 1.3659 | |

## 7% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.75 | 0.598 | 1.04167 | 0.29167 | 1.254 | 2.182 | 3.741 | 66.04 | 56.65 |
| 0.742 | 0.586 | 1.04485 | 0.30285 | 1.266 | 2.142 | 3.536 | 62.41 | 56.65 |
| 0.747 | 0.613 | 1.04284 | 0.29584 | 1.219 | 2.317 | 3.917 | 69.14 | 56.65 |
| 0.743 | 0.603 | 1.04445 | 0.30145 | 1.232 | 2.263 | 3.754 | 66.27 | 56.65 |
| 0.742 | 0.604 | 1.04485 | 0.30285 | 1.228 | 2.278 | 3.760 | 66.38 | 56.65 |
| 0.743 | 0.608 | 1.04445 | 0.30145 | 1.222 | 2.303 | 3.820 | 67.44 | 56.65 |
| 0.734 | 0.613 | 1.0482 | 0.3142 | 1.197 | 2.410 | 3.835 | 67.69 | 56.65 |
| 0.742 | 0.604 | 1.04485 | 0.30285 | 1.228 | 2.278 | 3.760 | 66.38 | 56.65 |
| 0.742 | 0.614 | 1.04485 | 0.30285 | 1.208 | 2.360 | 3.897 | 68.79 | 56.65 |
| 0.744 | 0.619 | 1.04404 | 0.30004 | 1.202 | 2.389 | 3.981 | 70.28 | 56.65 |
| | | | | | | | | |
| 0.743 | 0.606 | 1.04451 | 0.30161 | 1.226 | 2.292 | 3.800 | 67.08 | |
| | | | | | | STD DEV | 2.05889 | |

## 15% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.735 | 0.626 | 1.04777 | 0.31277 | 1.174 | 2.525 | 4.036 | 70.48 | 57.26 |
| 0.738 | 0.624 | 1.04651 | 0.30851 | 1.183 | 2.481 | 4.020 | 70.21 | 57.26 |
| 0.734 | 0.611 | 1.0482 | 0.3142 | 1.201 | 2.392 | 3.806 | 66.48 | 57.26 |
| 0.725 | 0.622 | 1.05216 | 0.32716 | 1.166 | 2.571 | 3.929 | 68.62 | 57.26 |
| 0.727 | 0.626 | 1.05126 | 0.32426 | 1.161 | 2.595 | 4.001 | 69.88 | 57.26 |
| 0.724 | 0.623 | 1.05261 | 0.32861 | 1.162 | 2.591 | 3.942 | 68.84 | 57.26 |
| 0.738 | 0.62 | 1.04651 | 0.30851 | 1.190 | 2.443 | 3.960 | 69.15 | 57.26 |
| 0.741 | 0.624 | 1.04526 | 0.30426 | 1.187 | 2.457 | 4.037 | 70.51 | 57.26 |
| 0.729 | 0.623 | 1.05037 | 0.32137 | 1.170 | 2.546 | 3.961 | 69.18 | 57.26 |
| 0.725 | 0.623 | 1.05216 | 0.32716 | 1.164 | 2.581 | 3.945 | 68.90 | 57.26 |
| | | | | | | | | |
| 0.732 | 0.622 | 1.04928 | 0.31768 | 1.176 | 2.518 | 3.964 | 69.22 | |
| | | | | | | STD DEV | 1.1317 | |

22% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.68 | 0.62 | 1.07529 | 0.39529 | 1.097 | 3.076 | 3.890 | 67.12 | 57.96 |
| 0.679 | 0.608 | 1.07588 | 0.39688 | 1.117 | 2.897 | 3.650 | 62.98 | 57.96 |
| 0.675 | 0.612 | 1.07824 | 0.40324 | 1.103 | 3.017 | 3.741 | 64.54 | 57.96 |
| 0.683 | 0.614 | 1.07356 | 0.39056 | 1.112 | 2.934 | 3.756 | 64.80 | 57.96 |
| 0.682 | 0.621 | 1.07414 | 0.39214 | 1.098 | 3.062 | 3.904 | 67.35 | 57.96 |
| 0.683 | 0.616 | 1.07356 | 0.39056 | 1.109 | 2.965 | 3.795 | 65.48 | 57.96 |
| 0.673 | 0.598 | 1.07944 | 0.40644 | 1.125 | 2.830 | 3.482 | 60.07 | 57.96 |
| 0.666 | 0.603 | 1.08375 | 0.41775 | 1.104 | 3.003 | 3.594 | 62.01 | 57.96 |
| 0.665 | 0.597 | 1.08438 | 0.41938 | 1.114 | 2.921 | 3.482 | 60.08 | 57.96 |
| 0.66 | 0.613 | 1.08758 | 0.42758 | 1.077 | 3.299 | 3.858 | 66.56 | 57.96 |
| | | | | | | | | |
| 0.675 | 0.610 | 1.07858 | 0.40398 | 1.106 | 3.000 | 3.715 | 64.10 | |
| | | | | | | STD DEV | 2.57627 | |

30% FINES:

| Ri | Ro | a | b | x | LN | sW | s | GRAMMAGE |
|---|---|---|---|---|---|---|---|---|
| 0.644 | 0.594 | 1.0984 | 0.4544 | 1.084 | 3.209 | 3.531 | 60.82 | 58.06 |
| 0.663 | 0.614 | 1.08565 | 0.42265 | 1.080 | 3.260 | 3.857 | 66.43 | 58.06 |
| 0.649 | 0.602 | 1.09492 | 0.44592 | 1.078 | 3.282 | 3.680 | 63.38 | 58.06 |
| 0.649 | 0.593 | 1.09492 | 0.44592 | 1.094 | 3.099 | 3.475 | 59.85 | 58.06 |
| 0.648 | 0.596 | 1.0956 | 0.4476 | 1.087 | 3.175 | 3.546 | 61.08 | 58.06 |
| 0.654 | 0.596 | 1.09153 | 0.43753 | 1.097 | 3.070 | 3.509 | 60.44 | 58.06 |
| 0.645 | 0.597 | 1.09769 | 0.45269 | 1.080 | 3.253 | 3.593 | 61.89 | 58.06 |
| 0.641 | 0.592 | 1.10053 | 0.45953 | 1.083 | 3.225 | 3.509 | 60.44 | 58.06 |
| 0.642 | 0.594 | 1.09982 | 0.45782 | 1.081 | 3.248 | 3.548 | 61.10 | 58.06 |
| 0.649 | 0.591 | 1.09492 | 0.44592 | 1.098 | 3.062 | 3.434 | 59.14 | 58.06 |
| | | | | | | | | |
| 0.648 | 0.597 | 1.0954 | 0.447 | 1.086 | 3.189 | 3.568 | 61.46 | |
| | | | | | | STD DEV | 1.98249 | |

# APPENDIX XI: BRIGHTNESS RAW DATA

## BLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| % BRIGHTNESS | 80.1 | 77.8 | 75.1 | 74.7 | 70 |
| | 80.3 | 77.6 | 75.3 | 74.9 | 70.4 |
| | 81 | 77.8 | 75.7 | 74.4 | 70.5 |
| | 81.1 | 77 | 75.6 | 74.3 | 71.5 |
| | 80.2 | 77 | 75.9 | 74.6 | 70.3 |
| | 79.3 | 77.6 | 75.5 | 74 | 70.3 |
| | 80.6 | 78.4 | 75.3 | 74.3 | 70.6 |
| | 80 | 77.8 | 75.7 | 74.1 | 70.7 |
| | 79.8 | 77.6 | 75.4 | 74.6 | 70.1 |
| | 79.8 | 78.1 | 74.8 | 74.3 | 70 |
| | 80 | 78.6 | | 74.3 | 70.3 |
| | 79.8 | 77.5 | | 72.4 | 69.8 |
| | 80.1 | 78.4 | | 74.6 | 71 |
| | 80.3 | 77.7 | | 73 | 70.5 |
| | 79.4 | 78 | | 74.2 | 70.4 |
| AVERAGE: | 80.1 | 77.8 | 75.4 | 74.2 | 70.4 |
| STD DEV: | 0.49 | 0.45 | 0.31 | 0.63 | 0.41 |

## TMP

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| % BRIGHTNESS | 46.5 | 46.5 | 47.9 | 43.7 | 40.2 |
| | 46.1 | 45.5 | 48.1 | 44.7 | 42.4 |
| | 45.8 | 46.1 | 46.9 | 44 | 41.4 |
| | 46.7 | 46.2 | 47.1 | 44 | 41.3 |
| | 46.1 | 46.5 | 47 | 43.9 | 41.1 |
| | 46.2 | 46.9 | 47.4 | 44.5 | 42.1 |
| | 45.2 | 45.8 | 47.2 | 44 | 41.5 |
| | 46.5 | 46.7 | 46.5 | 43 | 41.3 |
| | 44.5 | 46.2 | 47.6 | 43 | 41.5 |
| | | 45.9 | 47.9 | 43.5 | 41.7 |
| | | 46.1 | 48 | 43.2 | 42.6 |
| | | 46.6 | 47.6 | 43.2 | 41.5 |
| | | 46.8 | 47.6 | 43.5 | 42.8 |
| | | 45.7 | 47.7 | 43.4 | 42.2 |
| AVERAGE: | 46.0 | 46.3 | 47.5 | 43.7 | 41.7 |
| STD DEV: | 0.66 | 0.42 | 0.45 | 0.51 | 0.66 |

# APPENDIX XII: TENSILE INDEX RAW DATA

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| TENSILE STRENGTH, | 5.05 | 5.30 | 6.40 | 5.80 | 6.50 |
| kg/15mm | 4.50 | 5.30 | 6.10 | 5.75 | 6.30 |
| | 4.50 | 5.80 | 4.50 | 5.00 | 6.70 |
| | 4.30 | 6.30 | 5.35 | 6.05 | 5.90 |
| | 4.80 | 5.00 | 6.10 | 5.70 | 7.00 |
| | 4.50 | 4.80 | 5.70 | 5.10 | 5.50 |
| | 4.10 | 5.85 | 5.30 | 5.40 | 6.20 |
| | 4.50 | 5.60 | 6.30 | 5.80 | 6.65 |
| | 4.60 | 5.10 | 5.20 | 5.40 | 6.25 |
| | 4.30 | 5.10 | 5.50 | 5.80 | 6.50 |
| AVERAGE: | 4.51 | 5.42 | 5.65 | 5.58 | 6.35 |
| STD DEV: | 0.25 | 0.44 | 0.56 | 0.32 | 0.40 |

TMP

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| TENSILE STRENGTH, | 0.31 | 0.52 | 0.72 | 0.69 | 1.08 |
| kg/15mm | 0.31 | 0.6 | 0.72 | 0.6 | 0.86 |
| | 0.26 | 0.5 | 0.66 | 0.68 | 1 |
| | 0.3 | 0.38 | 0.76 | 0.84 | 0.94 |
| | 0.22 | 0.47 | 0.66 | 0.64 | 0.89 |
| | 0.36 | 0.5 | 0.74 | 0.79 | 0.97 |
| | 0.35 | 0.54 | 0.76 | 0.82 | 0.81 |
| | 0.24 | 0.5 | 0.68 | 0.82 | 0.92 |
| | 0.31 | 0.52 | 0.66 | 0.8 | 0.94 |
| | 0.33 | 0.52 | 0.68 | 0.82 | 0.98 |
| AVERAGE: | 0.30 | 0.51 | 0.70 | 0.75 | 0.94 |
| STD DEV: | 0.04 | 0.05 | 0.04 | 0.08 | 0.07 |

UNBLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| TENSILE STRENGTH, | | 4.80 | 4.80 | 5.50 | 4.90 |
| kg/15mm | | 4.70 | 4.50 | 5.30 | 5.25 |
| | | 4.80 | 4.50 | 5.10 | 5.81 |
| | | 4.40 | 4.30 | 5.60 | 5.50 |
| | | 4.50 | 5.10 | 4.80 | 5.60 |
| | | 4.20 | 4.80 | 4.80 | 5.00 |
| | | 4.10 | 5.00 | 5.40 | 5.81 |
| | | 4.60 | 5.10 | 5.40 | 5.00 |
| | | 4.10 | 4.80 | 4.60 | 5.60 |
| | | 4.70 | 5.20 | 5.00 | 4.90 |
| AVERAGE: | | 4.49 | 4.81 | 5.15 | 5.34 |
| STD DEV: | | 0.26 | 0.28 | 0.32 | 0.35 |

# APPENDIX XIII: BURST INDEX RAW DATA

## BLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| BURST, psi | 29.5 | 42 | 41.5 | 41.5 | 43 |
| | 31.5 | 42 | 42 | 42.5 | 49.5 |
| | 32.75 | 38 | 40.5 | 47.5 | 44 |
| | 35.75 | 39 | 44 | 47 | 33 |
| | 33 | 35.5 | 45 | 42.5 | 47 |
| | 29.5 | 39 | 44.5 | 46.5 | 45.5 |
| | 30 | 38 | 48 | 47 | 46 |
| | 31 | 35 | 41 | 40.5 | 40 |
| | 35 | 39.25 | 43.5 | 39.5 | 43.5 |
| | 32.5 | 41 | 48 | 40.5 | 44 |
| AVERAGE: | 32.05 | 38.875 | 43.8 | 43.5 | 43.55 |
| STD DEV: | 2.06 | 2.28 | 2.54 | 2.99 | 4.26 |

## UNBLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| BURST, psi | | 25.5 | 37 | 41 | 47.5 |
| | | 28.5 | 35.5 | 36 | 44.5 |
| | | 35.5 | 27 | 38.5 | 39 |
| | | 31.5 | 35 | 41 | 41.5 |
| | | 31 | 37.5 | 42 | 44 |
| | | 28.75 | 36.5 | 42 | 36 |
| | | 30 | 39.5 | 46 | 42.5 |
| | | 30 | 37.5 | 40.5 | 41.5 |
| | | 29.25 | 38 | 38.5 | 43.5 |
| | | 30 | 36.75 | 40 | 39 |
| AVERAGE: | | 30 | 36.025 | 40.55 | 41.9 |
| STD DEV: | | 2.41 | 3.24 | 2.52 | 3.12 |

# APPENDIX XIV: TEAR INDEX RAW DATA

## BLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| AVERAGE TEARING FORCE, mN | 4.8 | 3.8 | 3.1 | 3.4 | 3.8 |
| | 4.4 | 3.6 | 3 | 3.4 | 3.4 |
| | 4.4 | 3.8 | 2.9 | 3.6 | 3 |
| | 4.2 | 4 | 3 | 3.5 | 2.5 |
| | 4.2 | 3.6 | 2.9 | 3.2 | 2.5 |
| | 4.6 | 3.5 | 3 | 3.5 | 2.75 |
| | 4.4 | 3.7 | 3.1 | 3.4 | 3 |
| | 4.4 | 3.8 | 3.1 | 3.3 | 2.63 |
| | 4.6 | 3.4 | 3 | 3.4 | 2.88 |
| | 4.5 | 3.6 | 2.9 | 3.6 | 2.5 |
| AVERAGE: | 4.45 | 3.68 | 3.00 | 3.43 | 2.90 |
| STD DEV: | 0.17 | 0.17 | 0.08 | 0.12 | 0.41 |

## UNBLEACHED KRAFT

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| AVERAGE TEARING FORCE, mN | | 5.36 | 5.82 | 4.55 | 3.73 |
| | | 5.09 | 5.36 | 4.55 | 3.92 |
| | | 5.27 | 5.27 | 4.64 | 3.73 |
| | | 5.09 | 5.45 | 4.64 | 3.73 |
| | | 5.09 | 5.63 | 4.36 | 3.73 |
| | | 5.27 | 5.55 | 4.55 | 3.82 |
| | | 5.18 | 5.36 | 4.55 | 3.91 |
| | | 5.36 | 5.73 | 4.45 | 3.68 |
| | | 5.18 | 5.45 | 4.64 | 3.77 |
| | | 5.18 | 5.55 | 4.73 | 3.82 |
| AVERAGE: | | 5.21 | 5.52 | 4.57 | 3.78 |
| STD DEV: | | 0.10 | 0.16 | 0.10 | 0.08 |

## TMP

| PERCENT FINES: | 0 | 7 | 15 | 22 | 30 |
|---|---|---|---|---|---|
| AVERAGE TEARING FORCE, mN | 0.25 | 0.45 | 0.55 | 0.73 | 1.06 |
| | 0.25 | 0.45 | 0.55 | 0.73 | 0.91 |
| | 0.25 | 0.45 | 0.55 | 0.64 | 0.65 |
| | 0.25 | 0.55 | 0.55 | 0.73 | 1.11 |
| | 0.25 | 0.55 | 0.55 | 0.73 | 0.88 |
| AVERAGE: | 0.25 | 0.49 | 0.55 | 0.71 | 0.92 |
| STD DEV: | 0.00 | 0.05 | 0.00 | 0.04 | 0.16 |

# PPENDIX XV: VARIOUS EQUATIONS USED

ATER RETENTION VALUE:

$$\% \text{ WRV} = \frac{\text{WET WT. AFTER CENTRIFUGING - OVEN DRY WEIGHT}}{\text{OVEN DRY WEIGHT}} \times 100$$

ENSITY:

$$\text{DENSITY, g/cm^3} = \frac{\text{GRAMMAGE, g/m^2} \times 0.0001}{\text{CALIPER, mils} \times (0.001 \times 2.54)}$$

'ENSILE INDEX:

$$\text{TENSILE INDEX, Nm/g} = \frac{\text{TENSILE STRENGTH, kN/m}}{\text{GRAMMAGE, g/m^2}}$$

URST INDEX:

$$\text{BURST INDEX, kPa-m^2/g} = \frac{\text{BURST STRENGTH, kPa}}{\text{GRAMMAGE, g/m^2}}$$

'EAR INDEX:

$$\text{TEAR INDEX, mN-m^2/g} = \frac{9.807 \text{ X FORCE TO TEAR SINGLE SHEET, g}}{\text{GRAMMAGE, g/m^2}}$$