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A Quantitative Study of the Effect of Cutting & Fibrillation on Certain Paper Properties

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A QUANTITATIVE STUDY OF THE EFFECT OF CUTTING & FIBRILLATION ON CERTAIN PAPER PROPERTIES

A

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INTRODUCTION

From the time of the invention of paper about the year 105 by Ts'ai Lun, the process of beating the pulp as a preliminary to forming a sheet of paper has been recognized as of prime importance.

Early papermakers did not concern themselves greatly with theories; it was enough to know the process necessary to produce the various combinations of long and short, slow and free stocks according to the paper being made. When chemists began to enter the mills, however, their attention was naturally drawn to this important aspect of beating, and to the relationship between cellulose and water in the beating cycle. This relationship is of such fundamental importance in the practice of papermaking that it has been subject to a myriad of published articles and discussions. Even yet, there is not complete unanimity amongst the so-called experts concerning this complex cellulose-water relationship in beating.

In order to explain the various known effects of beating, there seem to be two distinctly different schools of thought to consider; those supporting the chemical aspects of beating, and those advocating the physical colloidal aspects of the beating action.

The Chemical Theory of Beating

The Chemical theory of beating proposed initially in 1920 by C. F. Cross and E. J. Bevan (1) suggested that during beating a fresh change takes place in the fibers as a result of their contact with a water-medium. The fibers are cut and fibrillated and at the same time the cell wall of the fiber absorbs water, passing into a condition of a gelatinous hydrate or slime. This hydrate is presumed to be a chemical compound of cellulose and water providing a strong adhesive which, upon drying, cements the structure together.

It has been found experimentally that beaten pulp is slightly more hygroscopic than unbeaten pulp, indicating that some hydrate is formed during the beating process. However, because there has been no definete experimental evidence as to the presence of such a hydrate, the slight excess of moisture in the beaten pulps can be satisfactorily explained by the fact that intensive beating has opened up the internal structure of the fiber, providing increased surface to absorb additional moisture. The theory that the hydrate was glue-like in character, increasing in quantity as beating proceeded, explained satisfactorily why sheet strength made from cellulose fibers also increased with beating. In fact, this chemical theory of beating was able to explain satisfactorily almost, if not all, of the practical beating phenomena known up to that time.

It did, however, have its shortcomings as were later proved by the advocates of the physical theory of beating.

The Physical Theory of Beating

Strachan, in an article published in 1926 (2) severely criticized the formentioned chemical theory of beating. He insisted that the taking up of water by pulp in beating should be termed "imbibition" and not hydration. He described the water content of paper stock as follows: (1) Water of suspension, in which the fibers float; (2) Capillary water held between the fibers and in the canals and pores; (3) Colloidal water composed of (a) Water of "imbibition" absorbed by the unbeaten fiber, and (b) Water of "hydration", or an increase of water of imbibition owing to beating.

He proposed that any water retained by the fiber is retained in a physical sense only.

In his experiments he found that upon drying both beaten and unbeaten pulps under carefully controlled conditions there was no evidence of any break in the curve relating moisture content to time, and consequently no evidence of hydrate formation in the strict chemical sense.

After describing the internal structure of the cellulose fiber as we know it today, Strachan proposed that the layers of compacted fibrils, being porous, allow water to penetrate into the fiber structure causing the fiber to swell. Upon subjection to beating action these outer layers are loosened and the surface becomes fibrillated. Hence, when the sheet of paper is made the fibers of the beaten stock are soft and fibrillated and lie and adhere together more closely than unbeaten fibers on the forming wire of the machine. Between the press rolls of the paper machine the fibers are squeezed into intimate contact according to their plasticity and degree of fibrillation.

In 1932, a Canadian investigator W. B. Campbell (3) proposed a different view of the mechanism of bonding. This became known as the "Partial Solubility" theory of fiber bonding. He advanced that during the formation of cellulose in nature, a precipitate is formed in the presence of water enabling the hydroxyl groups of the cellulose molecule to have attached molecules of water. As the fiber dries, the hydroxyl groups would be freed from water and their residual valences would be mutually satisfied by those adjacent cellulose molecules, thus causing the formation of secondary valence bonds. When the fibers are rewetted some of these bonds are broken and some hydroxyl groups reattach themselves to water, giving a more flexible form of structure. Campbell maintained that because of this "partial solubility" the molecules of cellulose when exposed on the surface of the fiber by beating were on the verge of solution. Thus they were endowed with a freedom which enabled the molecules of adjacent fibers to so orient themselves that, upon drying, many of their hydroxyl groups could bond together by means of secondary valance forces.

In conjunction with Campbell's theory it is interesting to note that in 1924 two Russian investigators Wislicenus and Gierisch (4) found that after breaking down cellulose by very fine grinding, 0.05-0.39 per cent of the cellulose became soluble in water and because the amount of ash in the dissolved portion was little more than that in the original paper, it was clear that some cellulose material had dissolved. Upon investigation of the undissolved material, however, they found a marked increase in the copper number and methylene blue absorption indicating that the degree of polymerization of dissolved portion was reduced and possibly that some carboxyl groups had been formed. Thus we cannot say with absolute assurance that the material in solution was actually cellulose.

In 1933 Campbell published a theory (5) which offers a plausible explanation for the joining together of fiber elements to a degree of proximity permitting the force fields of the elements to react and bond. During the drying of the sheet, water is located in the microcapillaries of the fibers and between fibers in the zones of close contact. According to Campbell's theory, surface tension pulls fibers and fibrils together during the drying process. Presumably the number of such points in the paper sheet would be very large and would depend upon such factors as the nature of the fiber, the type and degree of beating action, and the pressure and duration of pressure during the wet pressing period.

This theory explains satisfactorily why well-beaten stock compacts so easily on drying, giving a hard, dense, strong sheet.

Campbell's theory has recently been supported by Van den Akker (6), who in 1952 published an article dealing with this aspect of beating. He showed that if an undried test sheet were frozen and the water consequently removed by sublimation in a freezer, the resulting dry sheet was bulky, opaque and weak. This indicates the absence of any force to pull fibrils into intimate contact enabling the force fields of the fiber to react.

Cottrall (7) published photomicrographs showing mildly beaten fibers almost completely devoid of fibrillation which still formed strong sheets of paper upon drying. He went on to minimize the importance of the external fibrillation theory and instead emphesis wet fiber pliability facilitated by the presence of hemicelluloses and internal fibrillation brought about by beating. He thus concluded that fibrillation was not alone responsible for the strength characteristics of a sheet of paper.

Thus it is evident that upon review of these above theories or investigations, with the possible exception of the cellulose hydrate theory of bonding which so far has no valid experimental basis, none of the physical theories of bonding account satisfactorily for the high rate of strength increase always encountered during the preliminary stages of the beating cycle.

In July 1943, James d'A Clark (8) published a modified theory of beating which could well be described as a composite theory of all the above observations.

He maintained that during the chemical and mechanical treatment involved in the preparation of pulp, the primary wall of the fiber, which is permeable to but not swollen by water, is partially cracked, rubbed loose or removed exposing the underlying surface of the fiber. In the case of wood pulps this underlying surface is the spirally wound outer layer of the secondary wall. When the fibers are almost completely covered with this primary layer, as is usual in unbeaten pulp, adjacent fibers in the wet web are prevented from adhering together on drying, thus giving poor strength characteristics.

As beating proceeds, however, this brittle primary wall is rubbed or sheared off as a result of the wetting and swelling action of the fibers. Hence the underlying outer layer of the secondary wall becomes more evenly fibrillated, which not only permits stronger surface tension effects to compact the sheet better, but also results in a greater amount of bonding surface.

When the beating action reaches a certain point a state is reached where the increase in bonding material is offset by decreased fiber length and a weakening of the fibers themselves by mashing. At this point the pulp reaches its maximum strength.

It seems safe to say that this composite theory of Clark's appears to account for all the observed facts known at present about the beating process. Also, it is felt that any exception to this, arising in the future, can be easily explained by modifications of this theory.

Cutting and Fibrillation

The phenomena and changes which take place when pulp is beaten and made into paper are many. This can be explained by the myriad of variables encountered in the beating process. It can be said, however, that the results of beating can be grouped for purposes of discussion into two variables according to pulp type and effect on fibers.

As is clear, artificial cellulose fibers do not respond to beating owing to their solid structure and their characteristic inability to fibrillate. Likewise, mechanical or groundwood pulp and most semi-chemical pulps do not have sufficient delignification of their structure to fibrillate easily. In consequence they do not respond well to the beating action. On the other hand, chemical pulps such as kraft and sulphite, characterized by lower yields, are delignified to the degree where beating facilitates fibrillation enabling bonds to be formed between the individual fibers which in turn promotes greater strength development.

Hence, lignin removal plays a major role in the subsequent strength development of any pulp when that pulp is subjected to the stress action of a beater.

Much of the lignin associated with the cellulose fiber is found in the thin outer layer of the primary wall of that fiber. In chemical processing of pulp, however, the function of the cooking liquor is to dissolve the major portion of the lignin which abides on the outside of the fiber's primary wall. That is, to dissolve the lignin situated in the true middle lamella region between two fibers, thus freeing the individual fiber from its neighbor fiber. This liberation of individual fibers through chemical action is of prime importance when chemical pulps are subjected to beating.

In the case of mechanical pulps the individual fibers are not liberated from one another in the true sense of the word. Grinding represents a physical process, which by means of such mechanical actions as rubbing, tearing, and breaking in the presence of water, the wood is reduced to various sizes (9). The fibers may remain in a state of multiple "fiber bundles" or be reduced to a state even smaller than the individual fiber itself. The product is obtained as a mixture of structure of pulverized wood suspended in water.

As previously stated, the primary cell wall of the individual fiber contains a good deal of lignin not dissolved during the pulping stage. This wall may be regarded as being a sheath of non-reactive material which binds the tightly wrapped spirals of reactive cellulose (fibrils) in its grip. In order to promote any fibrillation from the outer layer of the fiber's secondary wall, the primary wall or constrictive "girdle" of lignin and hemicelluloses must first be removed. This removal is accomplished during the initial stages of the beating cycle.

The practical value of such knowledge of the cellulose fiber and its constituent structure lies in the better understanding of the beating mechanism and of the variety of influences which must be overcome during the beating action.

Broadly speaking the beating process is not effective unless carried out with water as the liquid medium. There are a few highly polar liquids which act like water but these are very few. It is essential that the liquid used be one which swells the fiber, otherwise only a cutting action will result with no fibrillation to speak of (10). Both qualities of the fiber are required to produce a satisfactory sheet of paper.

In short, using water as the carrier medium, two basic actions are accomplished during the beating cycle. (1) The fibers may be cut and (2) the fibers can be split or unravelled (11). The extent to which each of these two actions prevail will, of course, vary with the type of equipment used to prepare the pulp.

If the strain on the fiber is great enough it will break. This phenomena is referred to as cutting and is closely related to fiber length. It is safe to say also that cutting has long been recognized as an objective of stock preparation because of its effect on sheet properties. When cutting occurs it is almost equally likely that it will be done very near the ends of the fiber rather than at or near the exact middle of the fiber. In fact, with the production of only a small amount of cut fiber debris, it becomes much more difficult, on the average, to cut a fiber anywhere except near the end (11). Thus our cutting process is mainly one of making the longest fibers a little shorter while diminishing the shorter fibers to a state of mucilage.

The unravelling of the fibers is probably the objective of that aspect of stock preparation known variously as hydration and fibrillation. Upon swelling the fiber, the fibril bonds are ruptured enabling some of the torn cellulose fabric to be dislodged longitudally from its position in the fiber, appearing externally as distinct fibrils. These ruptured parts which appear as fibrils tend to be long and narrow and show a fiber-like appearance of their own. This conversion of internal surface to external leads to greater possibilities of contact among the fibers and hence to greater strength. It seems, therefore, that swelling of the fiber is required to allow fibrillation, and that fibrillation first appears after a long period of beating.

Thus, in practical beating operations both cutting and fibrillation are required in order to produce a satisfactory sheet of paper. The best that can be done is to regulate the beater roll pressure and clearance so that the balance between cutting and fibrillation is thrown one way or another. It seems that for maximum strength the average fiber length should be impaired as little as possible and at the same time fiber surface be subject to a bruising or rubbing action.

It is obvious that long fibers present much more area of contact for bonding than do short fibers and hence should produce stronger paper. Short fibers or fines, however, can act to a large extent to bridge spaces between long fibers where, otherwise, contact would not have been possible. Cutting of the fibers, therefore, seems to be a thing to be avoided except insofar as the presence of fines is necessary to obtain good formation. Thus the long-fibered portion of the pulp acts as the skeleton of a sheet, while the fines serve to fill in the interstices between the skeletal fibers thereby increasing sheet density.

It should not be taken from the above discussion that the principle aim of beating is to eliminate the formation of "fines" or cut fiber altogether. This is a grave misconception. The formation of fines in the beater is an absolute necessity, improving the sheet properties both optically and strength-wise. It should be shown, however, that the presence of too high a proportion of fines to long-fibered material can be detrimental to the physical properties mentioned.

Stress/Strain Rheology

Up to this point, this paper has simply dealt with a sequence of beating theories. The physical and chemical theories of the beating action have each been reviewed along with basic considerations dealing with the fibrillation and cutting action on the fiber.

It seems necessary now to relate these theories to the physical properties of the test sheet and to elaborate further upon the influences imposed on the sheet by fibrillation and cutting degree.

Basically, any physical strength test applied to a sheet is a measure of the stress/strain relationship of the fibers in that sheet. For example the tensile or breaking length test applied to a sheet is a measure of the elongation of the fibers with constant stress up to a point where rupture occurs. At this point the load acting on the sheet overcomes the fiber forces opposing it, causing fiber breakage and bond slippage to occur.

It has been shown by Van den Akker and coworkers (12) that when paper was subjected to rupture stress, about 65 per cent of the fibers involved in the rupture of the paper were actually broken. This figure will vary of course depending upon the fiber angle to the plane of strain, the degree of sheet wet pressing and on beating time. They maintain that fiber-to-fiber bonding is the most important factor in the tensile strength of ordinary paper, and that the strength of the fibers themselves is of secondary importance. In the tearing strength test, however, the situation is different. Here the strength of the fibers is considered to be of greater importance than the fiber-to-fiber bonding.

It seems therefore, from the above observations, that a reasonable balance must be reached between fiber strength and fiber-to-fiber bonding in any test sheet. Clearly, the more surface area introduced on beating, the greater the possibilities regarding the internal bonding of a sheet. Yet, fiber dimension also plays a major part in the subsequent strength development of a paper sheet as it is clear that long fibers possess more inherent strength than do short fibers.

The question must then be asked; is there an optimum point which must be reached between average fiber length and fiber-to-fiber bonding in a sheet, and how critical is fiber length on the stress/strain relationship of paper?

This question was studied by A. P. Arlov and discussed at the 1957 Cambridge Symposium of Papermaking Fibers (13). He investigated the effect of fiber length on the shape of stress/strain curves produced by various beating apparatuses. Pulp was beaten in a PFI mill, an L & W beater and a Valley beater to approximately the same breaking lenght after which it was fractionated in a Bauer-McNett classifier. The distribution of fiber length was measured and pulp beaten in the PFI mill was found to have the largest average fiber length, while the L & W beater pulp had the smallest average length.

He then drew normalized stress/strain curves for paper from whole pulp beaten in the three apparatuses. The PFI mill pulp, having the longest fibers produced a paper whose normalized stress/strain curve was located between those of the two other beaters. Thus, the curve shape is no simple function of fiber length. He goes on to say that the surface condition of the fibers is one of the main factors determining the degree of fiber-to-fiber bonding and that this factor will vary significantly between any two beating apparatuses.

He does not, however, discount fiber length entirely from the stress/strain relationship of a paper sheet. He maintains that there is a contribution from fiber length regarding the shape of stress/strain curves.

In order to clarify the effect of fiber length on curve shape, stress/strain curves were recorded for paper from the fraction of pulp collected in the four compartments of the classifier. Curves representing the normalized stress/strain curves from the four fractions of the beaten pulp showed that the shape parameter increased with decreasing fiber length. In short, it required more stress for a given amount of elongation with decreasing fiber length.

The above mentioned shape parameter can now be applied to sheet stiffness. The greater the sheet parameter, the greater the initial slope of the stress/strain curve. Consequently, the addition of fines to a pulp increases the stiffness and hardness of a sheet made from that pulp. Also, the more area beneath the curve, the tougher the sheet. This can be explained by the fact that increased fines content render a better distribution of bonding within the sheet, thereby making the sheet more isotropic with regard to strength properties.

The principle here is a basic one. The addition of fines tend to increase sheet strength, and the shape of a sheet's stress/strain curve gives a clear insight into the strength characteristics of that sheet. Yet, strength increases, with fines addition, does not continue indefinitely. The sacrifice of fiber length for fiber bonding can proceed only to a certain point. A point is reached where further addition of fines to a pulp brings about strength decreases. At this optimum point the sheet reaches its maximum strength.

Fiber Length

It can be said that the production of fines is a direct consequence of the beating action, the magnitude of which depends upon the extent of beating and on beater roll pressure.

Let it be assumed now that in a given pulp the degree of hydration or fibrillation is approximately the same for all fibers, regardless of their size. If this be so, differences between two samples of the same pulp, each having equal beating duration, will be the result of fiber length differences only. Hence, differences in average fiber length predominates when test sheet properties of this type are compared.

What is meant by the expression "average fiber length"? A brief examination of the literature reveals that almost every authority has his own, usually unexplained, ideas on the question. For example, the average fiber length of spruce varies from 0.74 millimeters to 3.48 millimeters depending on which method was used for the length determination. This is due to the fact that there are a variety of ways to determine this average including the numerical average length of the fibers, which is much affected by the lower limit of the length of the particles considered to be "fiber", the weighted average length by length, by projected area, by volume, and by true weight. Klemm (14) regards any fiber less than 0.10 millimeters as "debris", while Grund and coworkers (15) consider this figure to be 0.30 millimeters.

Since the thickness of the average paper is in the vicinity of 0.10 millimeters there is some reason for saying that any fiber whose length is below this figure should be regarded as "fines". This is because material shorter than this cannot sensibly be held to contribute to the fiber length, and whereas this fine material has an important influence on the overall pulp quality, as will be discussed later, obviously it should be classified as a filler.

Thus for the purposes of this paper, a fiber will be defined as an element of fibrous material having a length exceeding 0.10 millimeters and a projected area of over 0.10 x 0.10 millimeters. Anything below 0.10 millimeters will be referred to as "fine" material.

What effects, therefore, does the relative amounts of "fines" and "fibers" have on various physical properties of a pulp? Just how important are the factors of fiber size and the distribution of fiber sizes in determining the physical properties of a sheet?

The Influence of Fines

1. Freeness

Freeness or slowness as it is sometimes called, is one of those terms in paper technology which possesses a multitude of definitions. Freeness, as generally thought of, describes the change in general character of stock during beating and is the result, of course, of many factors. Such factors include hydration or fibrillation, a shortening of the fibers, and the accumulation of various kinds of debris or mucilage in the stock. It is the effect of these factors on pulp character which is measured by the various types of freeness testers in use today.

Yet, to determine the actual effect of fiber length on freeness is by no means a trivial task. The majority of such studies on drainage have used different fiber length samples obtained through fractionation of the original pulp, yet these have been hampered by side effects such as fibrillation, hence eliminating the fact that only the effect of fiber length was being investigated.

In a very interesting investigation, Reed (16) classified his pulp by the regular Bauer-NcNett procedure, separating the longest fibers from the remaining portion of the pulp. These fibers were then made into sheets and pressed to 65 per cent moisture content. This moisture content was selected because it was known that no appreciable fiber-to-fiber bonding occurs in excess of 60 per cent moisture still present in the sheet. The sheets were then cut into four different widths: 1/16, 3/16, 1/4, and 3/8 inches; the uncut sample was also retained and studied. The samples were then dispersed with slow stirring to avoid any fibrillation and then subjected to various freeness testers. Reed's data indicates that average fiber length has only a slight effect upon drainage time, which increased with a decrease in fiber length, while samples of differing fiber length obtained by fractionation of the pulp showed an appreciably large change in drainage time with fiber length.

This data is supported by Clark (17) (18) in his investigation of fines on the physical properties of various pulps.

In work done on Eucalypt kraft pulp beaten in a Lampon mill, Murphy (19) concluded that the amount of fines in beaten stock may be related to freeness. The removal of fines after beating caused an enormous rise in freeness, the screened pulps showing higher freeness values than were obtained for the unscreened, unbeaten pulp as measured by a Canadian Standard Freeness tester. The addition of extra fines to the beaten pulp caused a freeness reduction by as much as 145 points.

It is thus clear that the ease of drainage is diminished by subdivision of the fiber.

Through the use of a Schopper Riegler type slowness tester, Brecht and Klemm (14) investigated the drainage rate of groundwood with increasing proportion of fines to fiber content. Analogous results were obtained with those of the formentioned investigations. The composition by weight in the suspension ranged from 100 per cent fibers to 100 per cent fines. To broaden the investigation the effect was also determined with addition of 15 per cent by weight of an unbleached, unbeaten sulphite pulp at 15° S.R. The slowness value was seen to increase with increasing fines content, while in the region of low and average fines content the addition of sulphite increased the slowness value, while with higher content of fines, the value was decreased.

2. Density

The apparent density of a sheet of paper, that is its weight per unit volume usually expressed as grams per cubic centimeter, is perhaps the most fundamental factor influencing paper quality.

In a 1942 article, Clark (4) discussed the influence of the wieghted average fiber length by weight on density. He showed that changing the fiber length had no effect whatsoever on the density of the sheets. This data represented test sheets made from cut viscose silk stuck together with a mucilage, and for beaten and unbeaten sulphite pulps. He also showed that when density was plotted against the logarithm of the beating rate, a linear correlation results, except occasionally at the beginning of the beating cycle where it was presumed that the primary wall of the fibers interfer, and occasionally at the end of the protracted beating period when the fibers become severely mashed.

While beating markedly increases the density of a dry sheet, Clark (17) reaffirmed his above report that density does not seem to be affected by fiber length when the latter is decreased from 3.00 millimeters to 0.50 millimeters. He showed, however, that the density was reduced slightly (3%) when the sheet was made from a mixture of equal parts of long and short fiber. He maintained that the length of the fibers play a minor role in influencing the density of a sheet as their surfaces are usually covered with fibrillae. He did not go on to give the effect of fines on sheet density, but admitted that their presence was a major factor.

In 1935 W. B. Campbell (10) looked to fibrillation as the cause for increase in sheet density. He reported that the subdivision of the fibers into fibrillae subdivided the water spaces or voids between the main fibers into many more smaller ones. Because of this the water in the sheet can and does exert a strong force on the sheet structure during the drying, drawing the structure closer together and therefore increasing the density.

Jones, Ross and Johnston (20) showed that the density of groundwood decreased steadily as relative fiber length increased. Similar relations held for sulphite, but the effect of fiber length was much less marked owing to greater flexibility of the fibers. They point out that density is probably influenced by fibrillation to varying degrees which is in direct accord with Campbell's theory.

It is clear then that there is considerable disagreement amongst the above papers as to the influence of fines on sheet density. It is safe to say, however, that fines do play a major role regarding this property.

3. Tensile Strength

It was pointed out by Doughty (21) that sheet density is an important factor in determining sheet strength. He proposed that density be replaced by solid fraction by volume and then went on to give a qualitative study of the tensile strength-solid fraction relation. He showed that tensile strength measured in a regular manner with increase in solid fraction in the test sheet, and that strength increases was due to an actual change in the surface condition (fibrillation) of the fibers, and also to those solid fraction increases dependent upon increased shrinkage, i.e.: decreased fiber particle size.

Doughty later published an article in 1932 (22) showing the effect of fiber length on the tensile strength of pulp test sheets at constant solid fraction. He used a black gum pulp in his short-fibered test sheets and spruce in his long-fibered sheet and showed there was no great differences in strength among the individual pulp fractions at any given solid fraction. He then plotted the ultimate tensile strength against the pressure on the wet sheet. Considering sheets made from both spruce and black gum, under any given pressure when wet, those from the short-fibered fraction were from 25 to more than 200 per cent stronger than those from the long-fibered fraction, depending on the exact pressure being used. This can be explained by the fact that the short-fibered pulp, pressed while wet under a given pressure, gives a sheet of higher solid fraction and therefore of greater strength than one of the longer fibered pulps.

To insure that his only variable was fiber length, Clark (4) undertook a procedure in which a quantity of bleached sulphite pulp was fractionated and only the material in the long fraction was further used. Sheets made of the long-fiber fraction were cut fine with a sharp knife and the pulp reclassified into several fractions. He found that tensile strength was proportional to $KL^{\frac{1}{2}}$, where L is the weighted average fiber length by weight. He then went on to say in a later article (18) that by varying the density of the dry sheets, with increasing pressure on the wet test sheets, the tensile strength could be shown to increase directly with the density.

Work on glass fibers was done by O'Leary and coworkers (23) in which the influence of fines was noted on the physical properties of the test sheets produced. It was necessary to avoid completely any trace of fibrillation on the fiber. Thus, a synthetic fiber such as glass was chosen to give complete cutting when subjected to the beating action. A sample of stock fiber as prepared for the paper machine was taken from the beater. Handsheets were made from a part of the sample, and another portion of it was run through a pulp classifier. Handsheets made from the fibers retained by the 65-mesh screen were found to have a tensile strength one fourth that of the handsheets made from the original stock. Handsheets made from the fibers retained on the 100, 150, and 200-mesh screens mixed together were so weak that the strength could not be measured. Handsheets made from the fibers from the 65-mesh screen mixed with those from the 100, 150, and 200-mesh screens were ten times as strong as the sheets from the original stock.

It is of interest to note that neither the paper made from the long fibers (65-mesh) nor that from the combined short fibers was as strong as the paper from the original stock. The explaination of this is that when the longest fibers were used no short fibers were present to bind the long fibers together, and when the short fibers were used, no long fibers were present to give the paper strength. With a combination of the long and short fibers the paper was ten times as strong as the paper from the original stock because all the "fines" were removed. This proves to be an important factor in the manufacture of glass paper and can be applied to natural paper when fibrillation influenceshave been eliminated. That is, the more "fines" there are in the paper past an optimum point, the weaker the paper becomes. This optimum amount is necessary, however, to bind the long fibers together.

Brecht and Klemm (4) carried out wet strength tests on groundwood at various proportions of "fines" to "fibers", and found strength to be dependent in particularly marked fashion upon the presence of an optimum mixture. The wet strength of those sheets consisting of fibers only, and that of sheets of pure "fines" was so small as to be impossible of measurment. The mixing of these two form components, however, brought about a measurable tensile strength in the wet sheets and a measurable tensile strength in the wet sheets and a maximum value was obtained at a definite proportion. He showed that with increasing content of fines the wet strength increased almost linearly, reaching a maximum with a mixture comprising approximately 50 per cent fiber and 50 per cent fines. With still greater proportion of fines the wet strength decreased steadily to zero with a fines content of 92 per cent. He then goes on to say that admixture of fines to fibers at first increases the dry sheet breaking length very rapidly, the maximum value being obtained with a lower fines content than in the case of the wet tensile strength.

Work was done at Western Michigan University by Nadelman and coworkers (24) which supported the above findings of Klemm and Brecht. Here a study of handsheet strength made from fiber fractions at various levels of the beating cycle was undertaken. By using a Bauer-McNett classifier they showed that tensile strength made from the fractions reached a relatively constant value after a certain beating period. Further evaluation of handsheets formed from these fractions gave a clear indication that tensile strength did not equal or exceed the strength shown by the whole pulp at any given degree of beating. This was explained by the fact that the various fractions did not have the binding influences of fines which was experienced by the whole pulp.

4. Tearing Strength

As is well known, beating produces a decrease in tearing strength, at least after a certain minimum of bonding has occured. This lowering of tear can be explained partly on the basis of a restriction or concentration of the tearing stress over a small area of the paper with increased bonding.

Galley (25) introduced an argument which indicates that without fibrillation the tear value of a pulp would increase with increased beating action. He pointed out that, omitting from consideration the decrease in average fiber length during beating, the flexibility of the fiber, increased during the beating cycle, might be expected to produce some degree of non-linearity in positioning the fiber. Such a positioning as a result of the beating should aid materially in diffusing stresses and thus increase tearing strength. This argument is, however, only speculative, as to omit any consideration of cutting during the beating cycle is an impossibility.

Nadelman and coworkers (24) showed in their fractionation tests that the long fibered portion of a pulp was superior in tearing resistance to that of the whole pulp as well as to the shorter fraction of that pulp. This indicates the extreme influence which cutting and "fine" concentration exhibit on the tearing strength of pulp.

Clark (4) reported that if the only variable in his test sheets was fiber length, the tearing resistance was proportional to $L^{3/2}$ where L is the weighted average fiber length by weight. He arrived at this relationship by plotting the tearing strength of a sulphite pulp and **viscose** silk pulp against fiber length on a log-log basis. The result was a straight line for each pulp and by measurment of their slopes the above relationship was derived.

Montigny and Zborowski (26) measured fiber length index, tear ratio, and Schopper Riegler slowness over a wide range of beating conditions for a bleached sulphate pulp. From data secured it was possible to derive an empirical relationship between fiber length index and Schopper Riegler slowness on one hand, and tearing strength on the other. The values of tear ratio fell in a straight line indicating that tearing strength was independent of slowness, yet dependent on fiber length.

Doughty (22)agreed with this fiber length dependence by pointing out that the resistance to tear of sheets of long fiber content is appreciably higher than those of short fibers at the same solid fraction. He was supported by Nadelman (24) and Brown (27) in this respect.

5. Bursting Strength

D. C. Murphy (19), in a 1954 Australian publication, investigated the effect of beating on the physical properties of a pulp, when those pulps were beaten in either a Lampen mill or a Valley beater.

He points out that in the case of a high alpha soft bleached sulphite pulp, the values for bursting strength in the Lampen mill are inferior to those obtained in the Valley beater. This can be explained by the fact that the Lampen mill tends to crush very soft pulps. When eucalypt kraft pulps are compared, however, it is clear that the Lampen mill develops much higher burst than does the Valley beater. This can be explained by the fact that the Valley beater produces more cutting and gross fiber damage than the Lampen mill which accounts for the inferior quality of the Valley beater stock.

He found, however, that Lampen mill beating produces slightly more fines than does the Valley beater when the two instruments were compared at the same freeness level. After screening he found the burst values slightly lower in each case while each underwent an enormous rise in freeness. The loss of strength, however, was not in proportion to the increase in freeness values. He showed that, by taking bursting strength as a typical property, screening entirely alters the relationship between burst factor and freeness. Clearly the addition of fines to a pulp has a slight adverse effect on bursting strength.

J. d'A Clark found a similar change in this relationship between burst and freeness when beaten long-fibered pulps were screened (18). Clark also showed (4) that when burst values of screened sulphite fibers devoid of fibrillation were plotted against fiber length, the result was a linear relationship. He found the burst factor to be accurately proportional to the weighted average fiber length by weight L. That is, burst factor equals KL where K is a proportionality constant.

Montigny and Zboroski (26) plotted burst factor and fiber length index against Schopper Riegler slowness for various beater runs of a standard kraft pulp. In each run, the values of the bursting strength passed through a maximum and then decreased with subsequent beating action. They showed, in effect, that bursting strength was exceptionally dependent on fiber length which supports Murphy's theory.

6. Folding Endurance

In 1954, Goldsmith and Higgins (30) investigated the effect of fiber length on folding endurance, reporting their results before the Australian Pulp and Paper Industry Technical Association. They found that fiber length exerted a very critical influence on folding endurance.

Preliminary tests were made on three eucalypt kraft pulps of very different ranges of fiber length, each beaten for the same period of time. They suggest at this point that fiber length might critically influence fold, and the effect was investigated further by fractionating the kraft pulps. They point out the existence of two distinct mechanisms which contribute to folding endurance. One of these was designated the "fiber length effect", the other the "inter-fiber effect". The effect of increasing fiber length was to increase the folding endurance while the inter-fiber effect acted in the opposite sense. They suggest that the fiber length effect can operate only in the presence of a certain minimum proportion of fines (inter-fiber effect), the removal of which destroys the bonding capacity of the fibers thereby causing the fold value to decrease. This was confirmed later when a eucalypt kraft pulp was beaten in a Valley beater and then fractionated on a 80-mesh screen. The fine fraction was added in various proportions to the unbeaten whole pulp with a subsequent rise in folding endurance.

Thus it was shown that the influence of the inter-fiber effect predominates over that of the fiber length effect in the ultimate determination of folding endurance, and that fine material contributes to the bonding between the longer fibers giving greater values of folding strength as the beating action of the pulp progresses.

This theory was supported by the findings of Nadelman and coworkers (24) in their work done at Western Michigan University. Upon fractionating a western kraft pulp in a Bauer-McNett classifier, evaluation of the handsheets formed from the fractions gave a clear indication that folding endurance of the component fraction did not equal or exceed the strength shown by the whole pulp at any degree of beating.

Klemm and Brecht (14) measured the effect of fines and fiber material on the folding endurance of groundwood pulp. The residue on a 50-mesh screen was denoted as fiber material while the concentrate of the suspension passing through the screen was labelled as fines. The fold value of various proportions of these two fractions were determined by means of the Schopper Naumann apparatus. The folding endurance was higher with a pure "fiber" sheet than with the "fines" sheet. The maximum value, however, was attained only when sufficient adhesive and bonding forces were introduced by admixture of about 20 per cent fines to the free fiber.

It was again evident that in order to attain a high fold value the pulp must contain sufficient amounts of fine material for inter-fiber bonding in addition to long flexible fibers.

7. Opacity

In an article written in 1942, Shirley Parsons (28) studied the effect of fiber dimensions on the optical properties of a paper sheet. She points out the fact that certain short-fibered pulps such as hardwood soda and groundwood are recognized as pulps of high opacity. However, other short-fibered pulps may have a low opacity even though their average fiber length may be as low as that of the hardwood soda. She explains this low opacity by the fact that the degree of bonding between fibers has a decided influence on opacity; the greater the degree of bonding between fibers, the lower the opacity. Hence the degree of "fines" to fibers in a pulp seems to be ofset by the bonding influences with regard to the opacity of that pulp.

Optical measurments were then made both on isolated fractions of pulps and on handsheets prepared from mixtures of those fractions. For each pulp that was fractionated, one mixture was prepared from the fractions recombined in the same proportions as they existed in the original pulp. Sheets were also prepared from the original pulp. In the case of a pulp which contained a large percentage of fines it was shown that the reflectivity of the sheet made from the recombined fractions was appreciably lower than that of sheets made from the original pulp. In the case of pulps that contained a small percentage of fines it was shown that the reflectivities of the two types of sheets were nearly alike. Thus it can be presumed with reasonable safety that the presence of fines tends to increase opacity values for a given pulp.

Through the use of a photoelectric opacimeter in experiments conducted at McGill University, Maass (29) investigated the influence of fiber length of sulphite test sheets on opacity values of different fractions. The pulp was classified by means of a Johnston screen classifier and four fractions collected. It was found that transmittence decreases while reflectance increases with decreases in fiber length. These findings are thus in direct accord with the above theories of Parsons.

8. Porosity

The porosity of a sheet may be defined as the volume of air in cubic centimeters transmitted per second per square centimeter of sheet under a pressure head of one centimeter of water.

It would seem only natural that the porosity of a sheet is greatly dependent on the "fines" content of that sheet insofar as air penetration is concerned. Long fibers arrest the passage of air to only a limited degree, while fines, when present between these long fibers, will almost certainly set up barriers to decrease this air flow.

In a very interesting investigation, Doughty (22) took two sulphite pulps, one a spruce and the other black gum and studied the effect of porosity with pressure used in forming various handsheets made from these two pulps. Black gum is relatively short fibered and hence differs markedly from the spruce in this respect. Various fractions of each pulp were prepared, handsheets made at varying pressures, dried, and then tested with a Gurley densometer. When porosity was plotted against the pressure used in forming these sheets for different fractions, the curves showed differences of a hundred to a thousand fold in porosity between sheets made up under the same pressure from the fine and coarse fractions of one pulp. It was thus concluded that fiber dimensions have a decided effect on porosity. Sheets of the same solid fractions showed from ten to one hundred times greater porosity when made from long-fibered than when made from short-fibered pulp.

This theory was supported by Klemm (14) in his evaluation of the effect of "fiber material" and "fines" on groundwood sheet properties. The residue on a 50-mesh screen he called fiber material while the concentrate of the suspension passing through the screen he designated as fines. These were mixed in varying proportions and the properties of these mixtures investigated. Porosity was determined by means of the Bekk apparatus in which decreasing values mean increasing porosity. The high porosity of the "fiber" sheets free of "fines" was strongly reduced by the admixture of fines, but no further decrease was obtained after 50 per cent fines content was reached in the mixture.

Jones and coworkers (20) plotted the logarithm of air transmission against the log of sheet density for various newsprint grades of paper. They reported that for low fiber length, air transmission falls off, probably owing to shrinkage indicated by increased density.

EXPERIMENTAL OUTLINE

EXPERIMENTAL OUTLINE

PURPOSE

The primary purpose of the experimental work connected with this study was an attempt to determine the effects of two important variables encountered during the pulp refining process.

The two variables referred to are those of cutting and fibrillation. The effects of fines and fiber mucilage were not considered during the course of this investigation.

Through simple methods the effects of both cutting and fibrillation variables were separated from a control or reference pulp. This was made possible through careful characterization and classification of the two variables, obtained from two distinctly different procedures applied to the control pulp. One procedure produced maximum cutting action with minimum fibrillation, while the other produced maximum fibrillation with minimum cutting.

Fibers thus treated were then added in quantitative amounts to a control pulp in order to determine their effects upon various paper properties.

It was felt that this process of "refining through addition" would prove to be a perfectly acceptable procedure to indicate the influence of these two variables when applied to a constant control pulp.

MATERIALS

The materials used during the course of this investigation included the following: a bleached Western softwood sulphite pulp, a nineteen inch guillotine type cutter, a Noble and Wood sheet machine, a laboratory (4.25 inch diameter rotor) Morden Slush-Maker pulping unit, microscopic slides, a Bausch and Lomb laboratory microscope, a slide projector, a map measurer, a Canadian Standard Freeness tester, a TAPPI disintegrator, a breaking length tester (Testing Machines inc.), an M.I.T. folding endurance tester, a mullen tester (B. F. Perkins and Sons Inc.), an Elmendorf tearing tester and cutter, and a Bausch and Lomb opacity meter.

EXPERIMENTAL INVESTIGATION

EXPERIMENTAL INVESTIGATION

PREPARATION OF CONSTITUENT PULPS

Initial laboratory work consisted of processing a Western softwood sulphite pulp in three distinctly different ways. A control pulp, pulp A, consisted of the untreated raw bleached form characterized by an exceptionally high freeness value of 744 milliliters and poor strength development. This pulp was classified as pulp A.

The second pulp, pulp B, consisted of the same bleached sulphite form, but processed in such a way as to give a maximum amount of cut fibers, with minimum development of fibrillation. Three hundred air-dry grams of pulp were placed in approximately six liters of water and dispersed by an Atlas press stirrer for approximately five minutes. Handsheets were then made from this five per cent consistency suspension. Each handsheet contained approximately twenty-five grams of oven-dry fiber, being produced and pressed on a laboratory Noble and Wood sheet machine. The pads were then cut with a nineteen inch guillotine cutter into strips one-eighth of an inch wide, diluted with six liters of water, dispersed by an Atlas Press stirrer, re-formed into handsheets, and again cut. This process of handsheet preparation, guillotine cutting, redispersion and handsheet preparation was continued over a range of twenty times with a noticeable resultant decrease in fiber length. A nineteen per cent drop in freeness from that of Pulp A resulted from the cutting action applied to the pulp mass. This pulp was then characterized and classified as Pulp B.

The third pulp, Pulp C, again consisted of the raw bleached sulphite form, but processed in an entirely different manner from that of pulp B. A four per cent consistency suspension containing approximately nine hundred grams of air-dry fiber was placed into a laboratory 4.25 inch Morden Slush-Maker

TABLE I

CHARACTERIZATION OF CONSTITUENT PULPS

TREATMENT	NUMBER OF FIBERS COUNTED	NUMERICAL AVG. FIBER LENGTH - mm	WEIGHTED AVG. FIBER LENGTH-mm	PER CENT ERROR
Cut	760	0.493	0.67	3.40
Fibrillated	770	2.800	3.31	3.30
Control	2500	3.480	3.74	2.50

pulping unit. The clearance between the bars on the rotor blade and attributing ring were placed at a maximum to give a minimum amount of cutting action to the fibers. The pulp was subjected to this Morden treatment for approximately eighteen hours with a resultant Canadian standard freeness value of 283 milliliters. This sixty-five per cent drop in freeness (from that of Pulp A) was attributed to the high degree of fibrillation received by the fiber mass during the course of Morden action. The pulp was then characterized and classified as Pulp C.

Chloroform was then added to all three forms of the pulp to guard against bacterial degradation. The constituent pulps were placed in air tight containers and stored for future use.

CLASSIFICATION AND CHARACTERIZATION OF THREE PULPS

Three slides from each constituent pulp were prepared, each slide representing a different test area of the pulp type suspension. Carboxymethylcellulose was added to each dilute suspension in amounts of approximately 0.35 per cent based on oven-dry fiber weight. This was added to improve fiber deflocculation, thereby aiding the subsequent fiber count of each slide.

Each slide was projected with approximately two hundred fibers being counted per slide. The projected pattern was traced on a large piece of coated board which served as the projection screen. This board was then removed and the fibers counted, utilizing a map measuring device.

A numerical average fiber length and a weighted average fiber length were determined for all three slides of each pulp type. The resulting averages are shown on Table I. In each case over seven hundred fibers were counted which is equivalent to approximately three per cent error in fiber length determination.

It should be kept in mind that the per cent probable error for the weighted average fiber length is less than that of the numerical or arithmetic average fiber length. This is important as the weighted average fiber length is perhaps the most significant value in fiber length data. Here the influence of the long fiber stock is emphasized, thereby eliminating false values brought about by the inclusion of fine material. Better correlation with actual fiber length is, therefore, obtained through the use of this procedure.

The per cent error was determined through the use of a TAPPI graph showing per cent probable error plotted against fiber count over a large fiber number interval.

HANDSHEET PREPARATION

The three constituent pulp types; cut, fibrillated and control were mixed in various proportions as is shown in Table II. A freeness value was obtained from each pulp mixture. Nine handsheets were then prepared from each suspension. Initially, sheets composed only of fibrillated and control pulp, and cut and control pulp were prepared, after which all three pulp types were mixed in various proportions for sheet preparation.

Prior to handsheet preparation the combined constituents were subjected to the action of a TAPPI disintegrator for approximately five minutes. This aided the mixing and subsequent fiber formation of the finished sheet.

Handsheets were prepared on a standard Noble and Wood sheet machine, each sheet weighing approximately 2.505 oven-dry grams. This sheet weight is equivalent to the standard TAPPI sheet prepared on a British sheet mold machine. All strength tests run per sheet were corrected for 2.505 oven-dry grams, thereby bringing all sheets tested to a common denominator in weight.

TABLE II

SHEET COMPOSITION - % By Wt.	BASIS WGT. 25x40-500	FREENESS-ML.	BREAKING LENGTH - METERS	BURST FACTOR	TEAR FACTOR	FOLDING ENDURANCE - DOUBLE FOLDS	OPACITY %
100 Control	43.4	744	728	2.90	76.9	-	74.6
80 Control - 20 Fibrillation	43.4	680	1215	6.40	109.6	1.3	73.5
60 " - 40 "	36.3	624	1525	8.50	142.5	2.5	82.4
40 " - 60 "	39.1	512	2155	15.90	200.0	9.2	78.4
20 " - 80 "	38.5	396	2790	20.4	163.8	17.9	78.4
100 Fibrillation	34.8	283	3310	25.9	143.0	31.3	84.7
100 Control	43.4	744	728	2.9	76.9	-	74.6
80 " - 20 Cut	46.8	709	812	4.0	102.7	-	69.5
60 " - 40 "	46.2	696	965	4.2	90.8	-	71.3
40 " - 60 "	44.5	636	963	3.5	53.4	-	74.2
20 " - 80 "	41.8	620	818	2.5	37.6	-	79.1
100 Cut	40.2	604	695	1.1	31.0	-	82.6
100 Control	43.4	744	728	2.9	76.9	-	74.6
80 " - 10 Fibril. - 10 Cut	45.6	715	1035	4.7	99.3	0.9	71.6
60 " - 20 " - 20 "	48.2	680	1170	6.1	113.0	1.6	68.7
40 " - 30 " - 30 "	46.6	650	1380	8.3	145.7	3.3	70.8
20 " - 40 " - 40 "	42.6	562	1545	10.2	125.8	3.7	75.5
0 " - 60 " - 50 "	43.4	475	1855	13.9	106.0	5.8	75.7

PHYSICAL TEST VALUES AT VARIOUS SHEET COMPOSITIONS

Prior to physical testing, all handsheets were allowed to reach a moisture equilibrium in a constant humidity room existing at fifty per cent relative humidity and a temperature of seventy-three degrees Fahrenheit.

The sheets were then tested according to TAPPI standards for opacity, folding endurance, mullen, tear and tensile strength, the results of which are shown in Table II.

DISCUSSION OF RESULTS

The weighted average fiber length of all three constituent types was determined according to TAPPI standard methods. The control constituent recorded the highest weighted average fiber length of the three types. This value was found to be 3.74 millimeters. The fibrillated constituent had a weighted average fiber length of 3.31 millimeters, which represented a decrease in fiber length of 9.5 per cent based on the control pulp. This clearly indicates that the control pulp, when subjected to the action of the Morden Slush-Maker pulping unit underwent a maximum amount of fibrillation development, with a relatively slight amount of cutting occurring during treatment.

The weighted average fiber length of the cut constituent was 0.67 millimeters, representing a decrease in fiber length of 82.5 per cent based on the control pulp. This again indicates that the cutting procedure used gave maximum cutting action to the fibers with a minimum amount of fibrillation development.

In each case, over seven hundred fibers were measured using a projected slide and a map measuring device to obtain the fiber length value. This resulted in a probable error of approximately 3.0 per cent. The length value

Fig. 1.

Control Constituent- Fiber length distribution

<u>Number of fibers per fiber length interval</u>

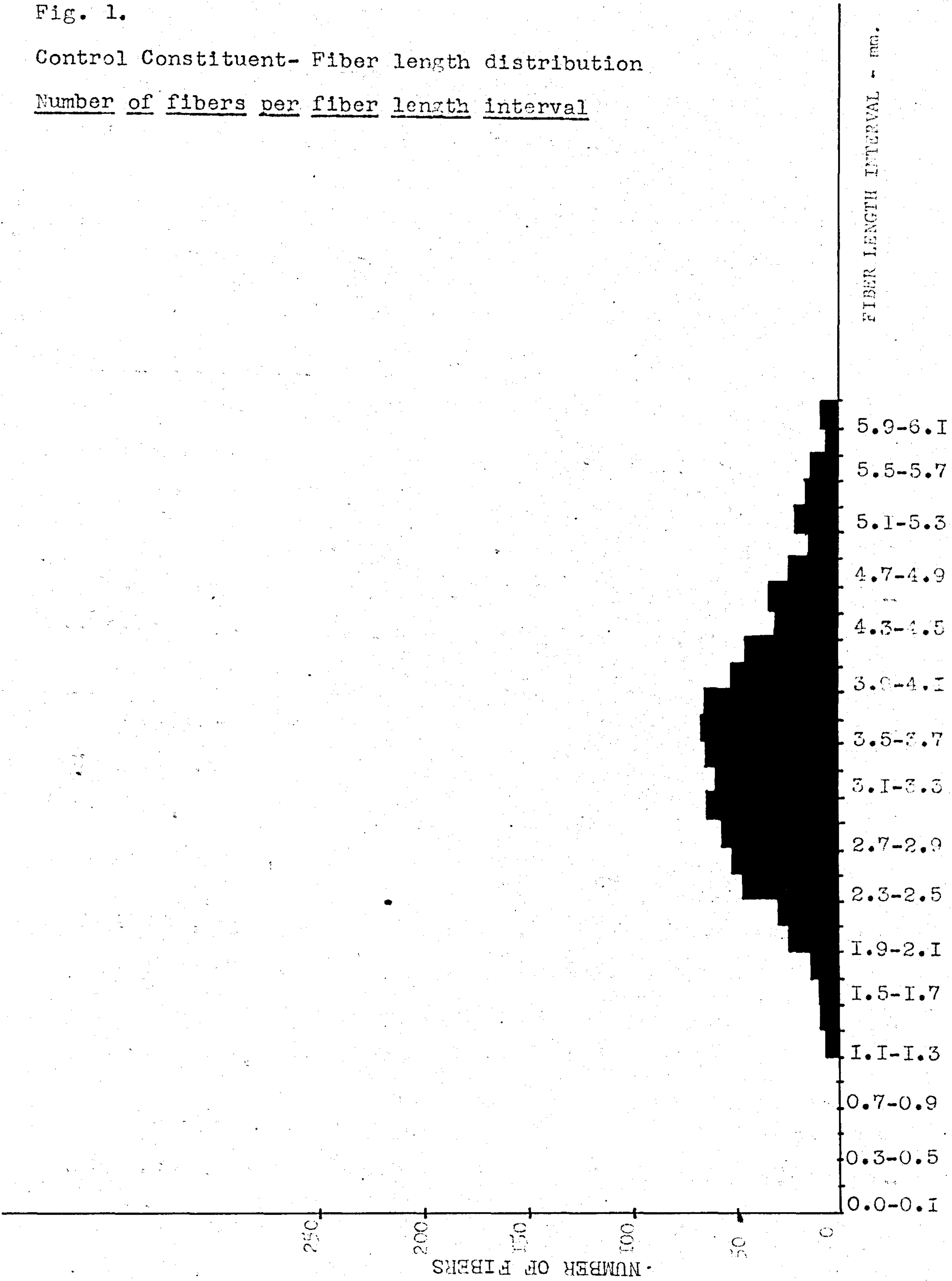


Fig. 2.

Fibrillated Constituent - Fiber length distribution

Number of fibers per fiber length interval

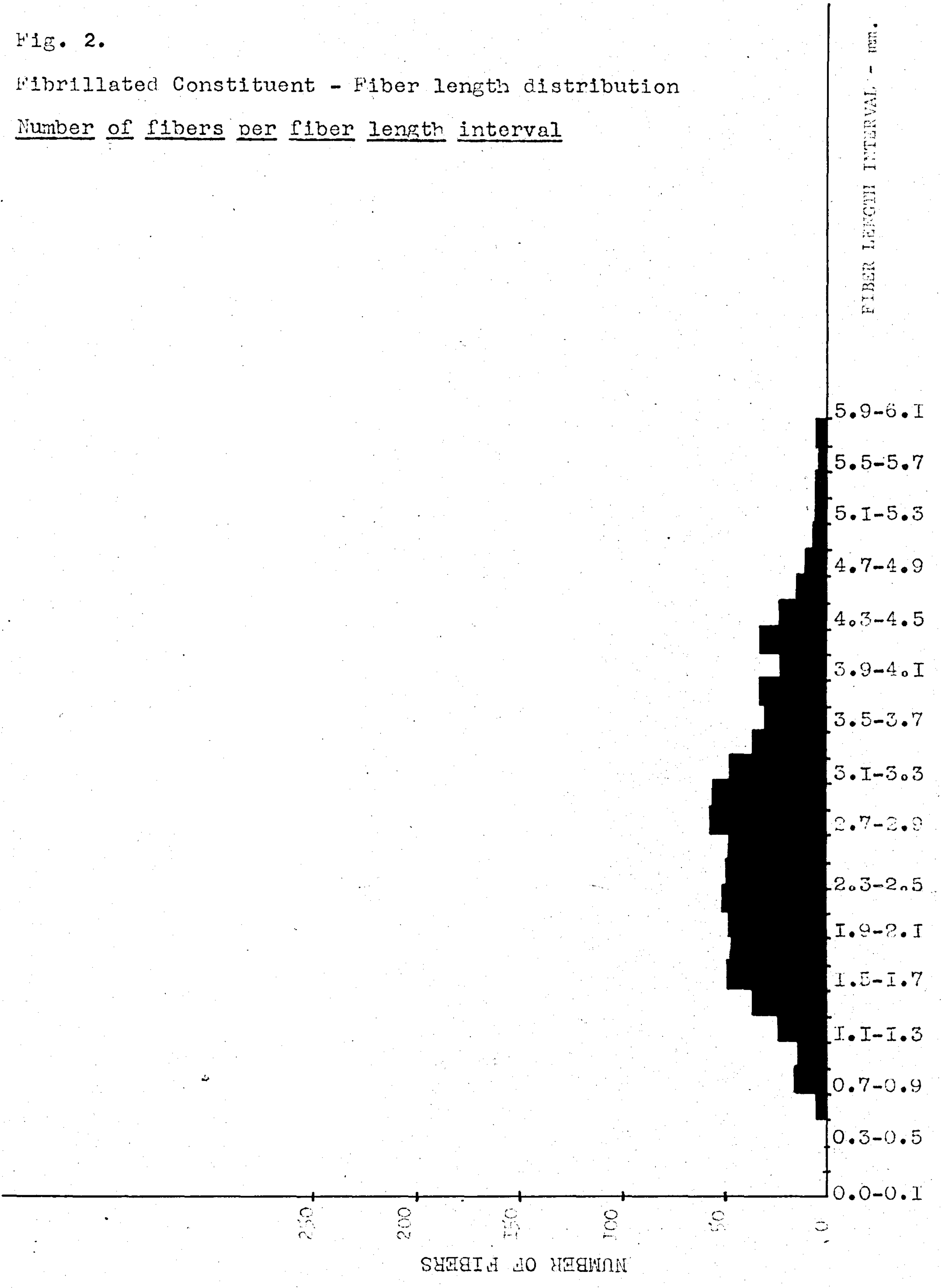
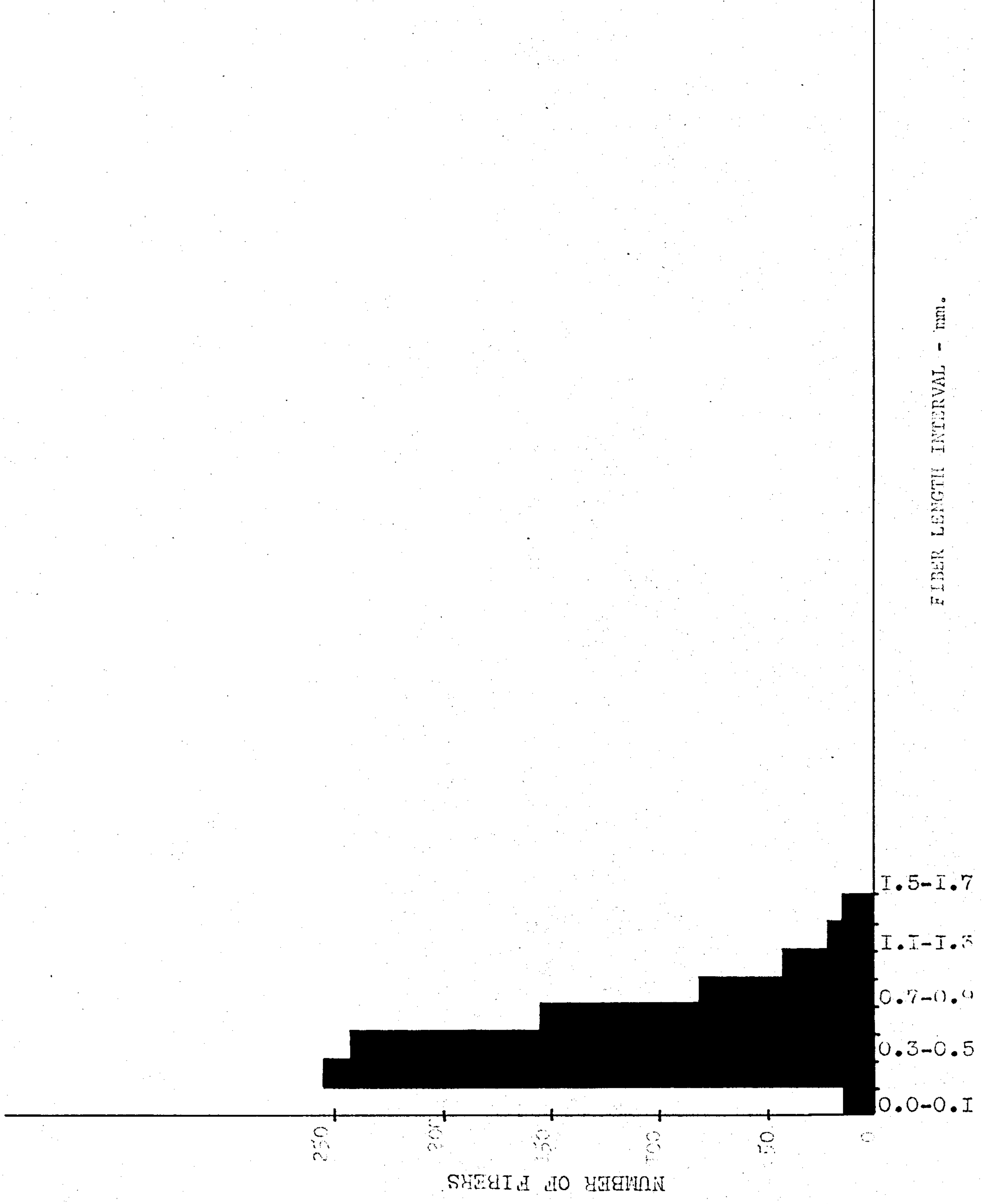


Fig. 3.

Cut Constituent - Fiber length distribution

<u>Number of fibers per fiber length interval</u>



of each fiber after measurement was recorded in a particular fiber length interval. The total number of fibers per fiber length interval was determined after which the weighted average fiber length value of the constituent was determined according to TAPPI standard methods. The total number of fibers per fiber length interval in millimeters was then charted for all three constituent pulps. This is shown in figures 1 - 3 inclusive.

A photomicrograph of each constituent type was then prepared in order to give the reader a better understanding into the treatments applied to the control pulp. The cut and fibrillated constituents are clearly evident when compared to the control constituent. These photomicrographs are shown in figures 9-11 inclusive.

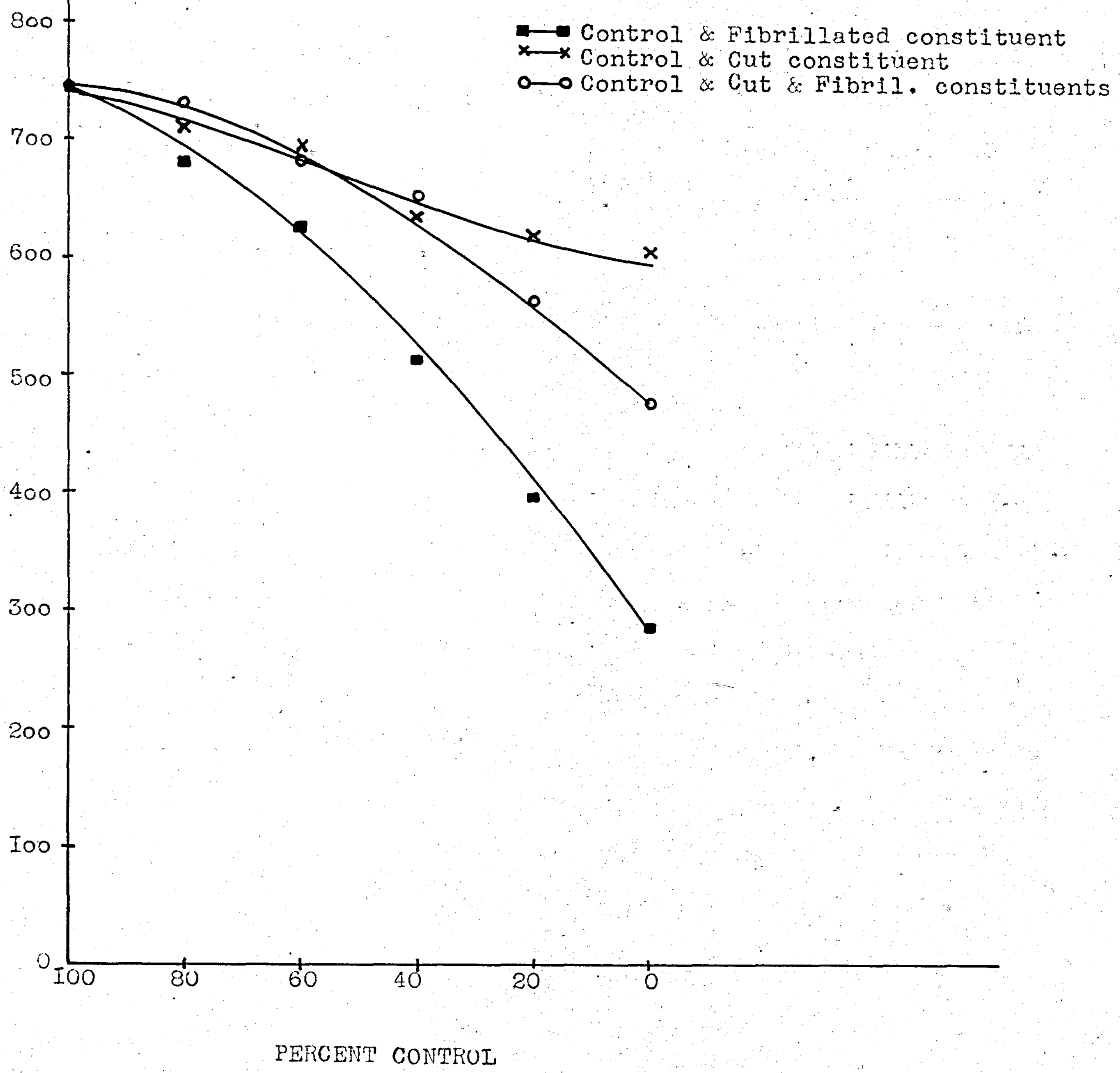
The effect of cutting and fibrillation on pulp Canadian standard freeness is shown in figure 4.

The freeness value of the control constituent was 744 milliliters while that of pure cutting and pure fibrillation was 604 and 283 milliliters respectively. It is clearly evident that the effect of both cutting and fibrillation will bring about a decrease in freeness, yet this decrease is more pronounced with fibrillation additions than when the cut constituent is added to the control pulp. When the fibrillation constituent was added to the control pulp in varying amounts up to eighty per cent, the freeness value underwent a decrease of 62.2 per cent based on control pulp. The addition of the cut constituent to the control pulp brought about a resultant drop in freeness of 18.8 per cent based on 100 hundred per cent control pulp.

The freeness value with fibrillation additions dropped decidedly faster than those values with additions of cut constituent. The freeness drop when both constituents were added in equal amounts to the control pulp was in-

Fig. 4.

Effect of cutting and fibrillation on freeness



termediate between that of pure cutting and pure fibrillation additions. It is interesting to note, however, that initially with equal addition of the two treated pulps, the drop in freeness value was very slight. The decrease in freeness between one hundred per cent and sixty per cent control with equal additions of the two constituents was only 8.1 per cent. This clearly indicates that a certain point in fibrillation and cutting action must be reached before pulp freeness will begin to drop to any extent. This indicates also that during the initial stages of beating or refining, fibrillation has little effect on freeness drop. That is, any decrease observed is due almost completely to the cutting action action applied to the fiber mass.

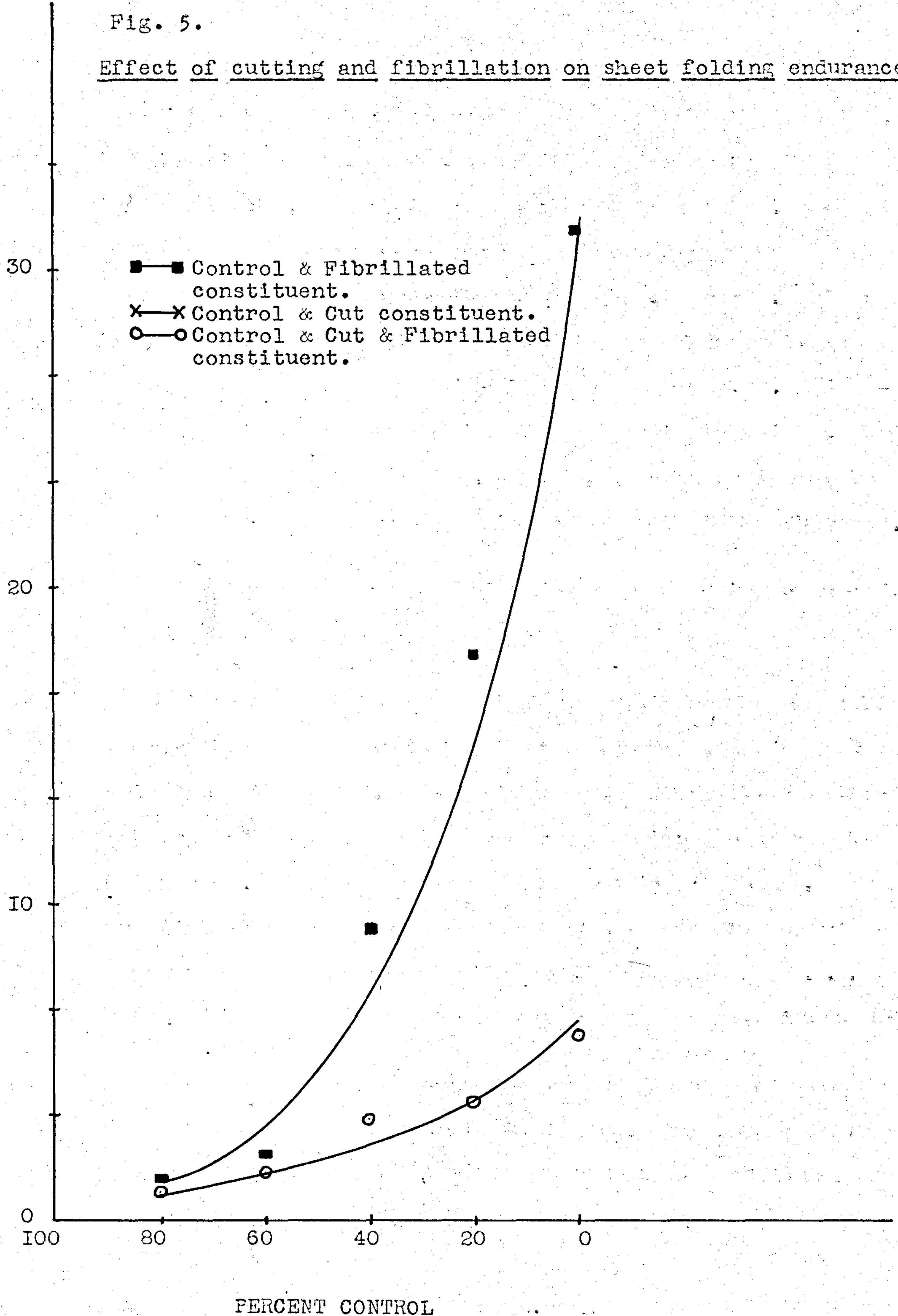
The effect of cutting and fibrillation on sheet folding endurance is shown in figure 5.

It is clearly evident that the influence of fibrillation on folding endurance is extremely favourable while the influence of cutting has a decidedly negative effect. Upon additions of the fibrillated constituent to the control pulp, the folding endurance value increased sharply to a maximum of 31.3 at one hundred per cent fibrillation constituent. No values were obtainable with additions of the cut constituent to the control pulp, as each test strip ruptured under the one kilogram load of the M.I.T. fold tester. This was also true of the one hundred per cent control test strips.

When fibrillated and cut constituents were added in equal amounts to varying proportions of the control pulp the folding endurance value reached a maximum at 5.8 double folds. This again indicates the detrimental effect that cutting treatment has on sheet folding endurance.

Fig. 5.

Effect of cutting and fibrillation on sheet folding endurance



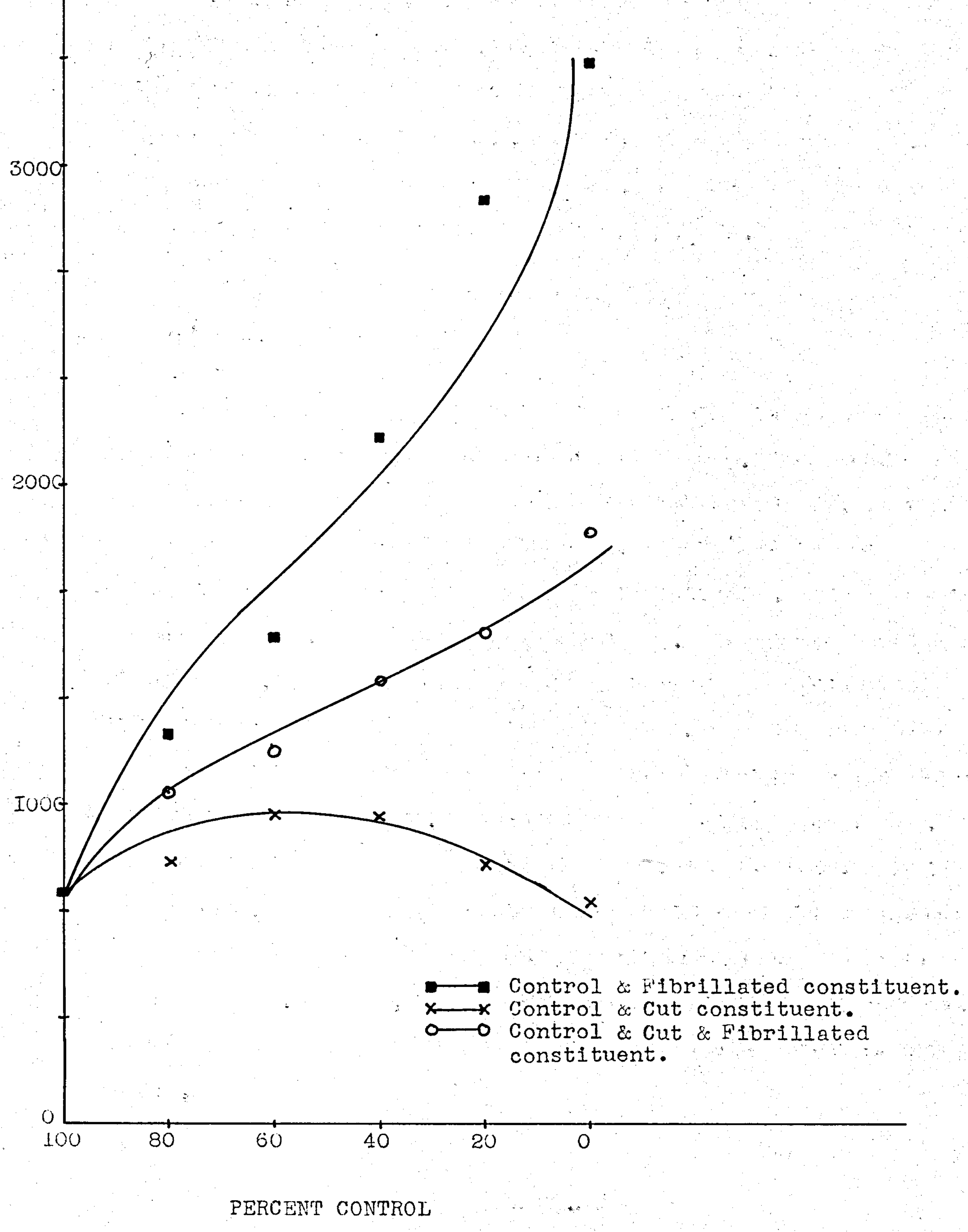
It thus seems clear that the necessary fiber treatment here is that of maximum fibrillation of the long fiber fraction in the pulp. Obviously fiber length is of utmost importance in the fold test as without it the folding endurance of a sheet will be at best, mediocre. It seems essential then, that for optimum folding endurance of any pulp, the fibers making up that pulp be subjected to as little cutting action as possible.

The effect of cutting and fibrillation on sheet tensile strength is shown in Figure 6.

It can be readily seen that cutting without fibrillation has a detrimental effect on the tensile strength of a paper sheet. Upon addition of varying proportions of fibrillated constituent to the control pulp, however, the breaking length underwent a sharp increase, reaching a maximum of 3310 meters at a composition of one hundred per cent fibrillation. This represents an increase of 354.5 per cent based on control pulp. The cut constituent on the other hand, when added to the control pulp in varying proportions did little to enhance the tensile qualities of the sheet. A maximum was reached with a composition of forty per cent cut constituent and sixty per cent control, yet this increase was only 32.5 per cent that of the original control pulp. When both fibrillated and cut constituents were added to the control pulp in equal amounts the value of the breaking length was intermediate between those values obtained when only pure cut or fibrillated constituent was added to the control pulp. Clearly, the larger the amount of fibrillated fibers added, the greater the breaking length value obtained, irrespective of cut constituent content.

Fig. 6.

Effect of cutting and fibrillation on sheet tensile strength



Obviously fiber-to-fiber bonding is of prime importance in the tensile strength of paper. Fiber length and the strength of the fiber itself seem to be secondary when compared to the former quality. Admixture of cut to fibrillated constituent in slight amounts would seem to increase the breaking length, yet past this optimum amount of cutting, only decreasing values will be observed.

Figure 7 shows the effect of cutting and fibrillation on sheet bursting strength.

A remarkable likeness can be seen when sheet mullen and tensile strength are compared. Again, a maximum value was obtained with a sheet composition of one hundred per cent fibrillation constituent. Upon addition of cut constituent to the control pulp a maximum value was again obtained at a sheet composition of forty per cent cut constituent and sixty per cent control, while with further addition of cutting, only decreasing values were obtained. Addition of both fibrillated and cut constituents to the control pulp in equal amounts, produced burst values which were intermediate between those values obtained when only the pure cut or fibrillated constituent was added to the control.

Clearly, fiber-to-fiber bonding plays the dominant role when optimum burst strength is desired. Mullen seems to depend little upon fiber length, or upon the strength of the fiber itself, even though slight amounts of cut constituent seem to be beneficial rather than a deterrent. Again, as with breaking length, once this optimum amount of cut constituent has been exceeded, only decreasing burst values will be observed.

Fig. 7.

Effect of cutting and fibrillation on sheet burst strength

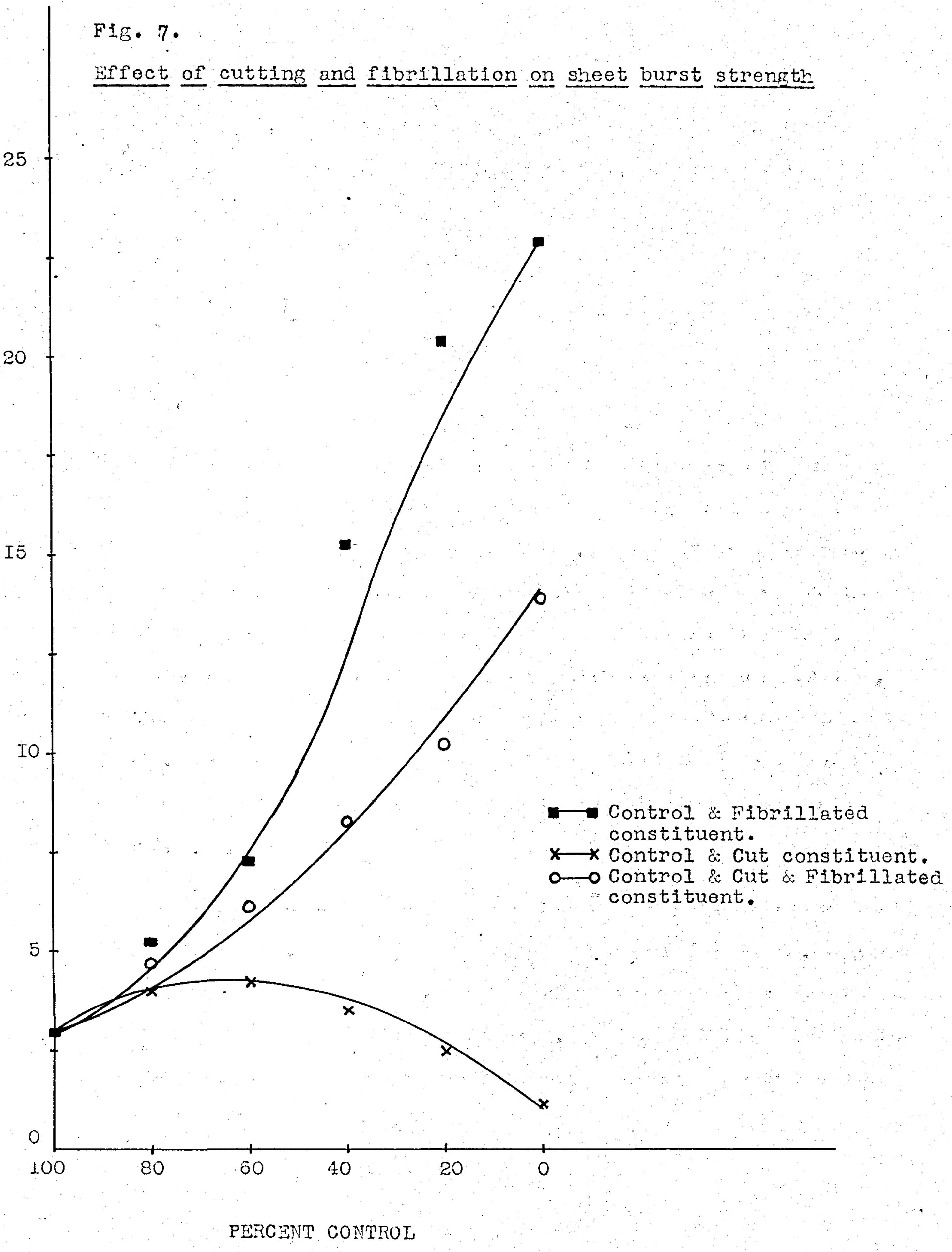


Figure 8 shows the effect of cutting and fibrillation on sheet tearing strength.

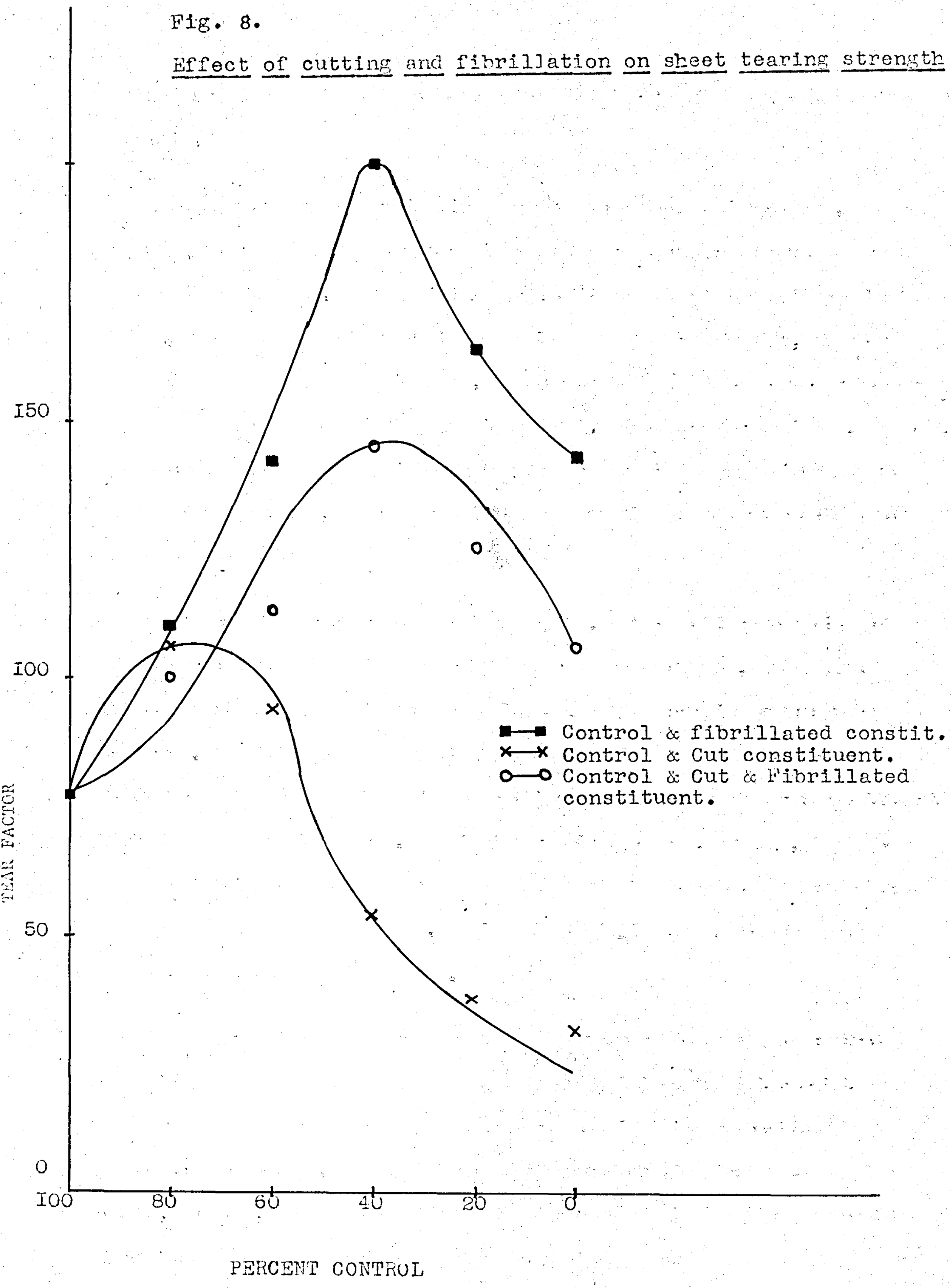
In all three cases the tearing strength rose to a maximum value, after which further addition of treated fiber to the control pulp caused a decrease in the tear strength. This initial strength increase can be explained by the initial tendency of the fibers to swell in the presence of water, thereby rendering the fibers more flexible. In such a pliable state more stress per unit area is required to tear the fiber sheet. Upon further refining, however, the increase in pliability is offset by a decrease in average fiber length due to fiber cutting, thereby causing a decrease in the stress required to tear the sheet.

The tear factor reached a maximum of 200.0 at a sheet composition of sixty per cent fibrillation and forty per cent control pulp, while with further addition of fibrillated constituent, only decreasing values were observed. Addition of cut constituent to control pulp produced a maximum tear factor of 102.7 at a sheet composition of twenty per cent cut constituent and eighty per cent control. It is interesting to note, however, that the highest initial tear values were shown when slight amounts of cut constituent were added to the control pulp. This clearly indicates the importance of limited cutting in the tear test.

When both fibrillated and cut constituents were added to the control pulp in equal amounts, the maximum tear value obtained lay intermediate between those values when only the pure cut or fibrillated constituent was added to the control. Initial tear values here were the lowest of all three cases, however, indicating the adverse effect which fibrillation has on the tear test when added to a fiber mass undergoing a decrease in average fiber length.

Fig. 8.

Effect of cutting and fibrillation on sheet tearing strength



Clearly, fiber length and the inherent strength of the fiber itself play the dominant role in the tear strength test. Fiber-to-fiber bonding seems to be only of secondary importance. The unravelling of the fiber causing this bonding clearly causes tear to decrease once the beneficial effect of fiber flexibility has been surpassed.

The effect of cutting and fibrillation on sheet opacity is noted in Table II.

Owing to the erratic nature of the test values received, the opacity of the test sheets were not reproduced in graphic form as were the other paper qualities measured.

Table II clearly indicates, however, that fibrillation without cutting brings about an increase in sheet opacity. Upon addition of fibrillated constituent to the control pulp, the opacity was seen to increase by 14.0 per cent, reaching a maximum of 84.7 per cent opacity at a sheet composition of one hundred per cent fibrillated constituent.

The addition of cut constituent to the control pulp brought about decreases in opacity during the initial set of additions, after which increases in opacity were noted reaching a maximum of 82.6 per cent opacity at a sheet composition of one hundred per cent cut constituent.

The addition of both cut and fibrillated constituents in equal amounts to the control pulp brought about values which were less clearly defined. The opacity decreased with initial additions, due in most part to the inclusion of cut constituent into the fiber mass. Opacity was then seen to increase reaching a maximum of 75.7 per cent at a sheet composition of both fifty per cent cut and fibrillated constituents. This latter increase can be explained by the high content of fibrillated constituent present in the fiber mass. Past a certain point, the fibrillated constituent was present in sufficient amounts to offset the adverse effect of the cut constituent, thereby causing the opacity to increase. The certain point mentioned above would seem to be approximately thirty per cent fibrillation constituent content, since past this point only increases in opacity were noted. Clearly, fibrillation has a beneficial effect on opacity as far as these results are concerned.

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CONCLUSIONS

CONCLUSION REMARKS

1. Fiber subdivision clearly brings about a decrease in sheet freeness. This decrease will be obtained easier and faster, however, if the pulp is subjected to fibrillation action rather than fiber cutting. In any case, before any freeness decrease will occur a certain degree of fibrillation or cutting must take place, after which a drop will be evident.

2. Fiber length exerts a very critical influence on sheet folding endurance. Clearly, fibrillation brings about an increase in folding strength while fiber cutting exerts a decidedly negative influence on this strength characteristic. Maximum fibrillation leads to maximum folding strength development.

3. Fiber cutting does little to enhance the tensile strength development of a pulp. The admixture of cut stock in slight amounts to fibrillated constituent, however, appears to increase pulp tensile strength, yet when added in excess of this, only decreasing strength values will result. Fibrillation is undoubtedly the requisite treatment when strong breaking length is sought.

4. The bursting strength of a pulp shows a remarkable similarity to that of its tensile strength development. Mullen is influenced by the same variables that effect the tensile test of a pulp. That is, fibrillation is the prime requisite for maximum burst, while fiber cutting exerts an adverse effect if it is extreme. As with tensile, however, a slight amount of cut stock appears to be beneficial to burst strength development.

5. Both fibrillation and cutting action play an important part in pulp treatment when a high tear value is required. During the initial stages of pulp treatment tear will rise to a maximum and then fall off as further treatment proceeds. Fibrillation seems to be of utmost importance for optimum tear development, but limited cutting is also required. Fibrillation without cutting brings about tear increases up to a point, after which some cutting is an absolute necessity. Too much of each will ultimately lead to decreasing tear factor values.

6. No concrete conclusions were reached concerning the effect of cutting and fibrillation on sheet opacity. Pure fibrillated stock gave greater opacity values than did pure cut stock, yet results were erratic in both cases. Clearly both types of treatment are necessary in any sheet, yet fibrillation appears to play the dominent role.

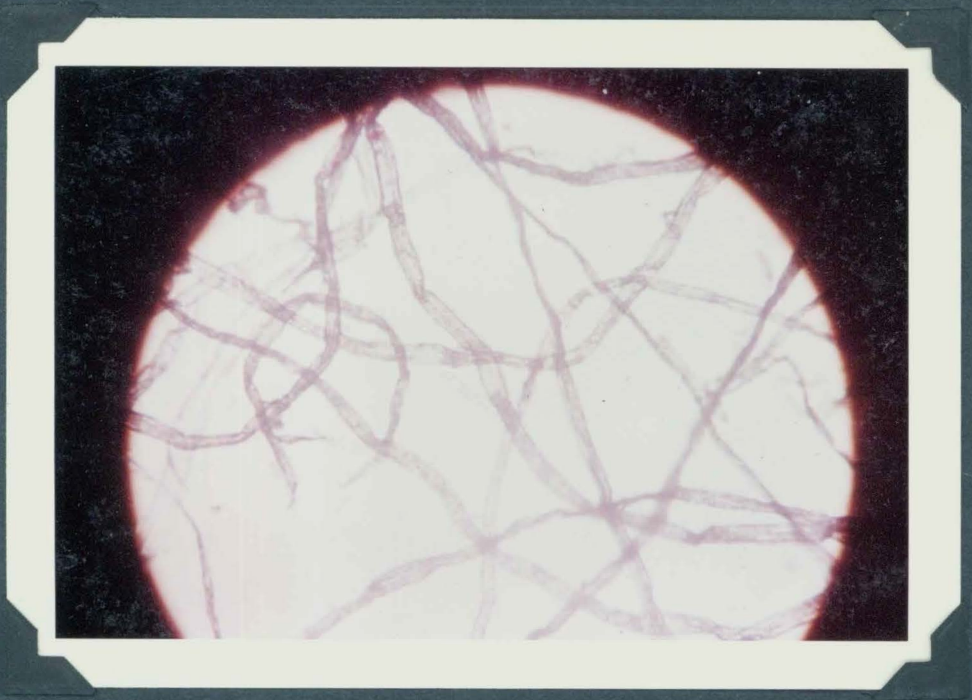
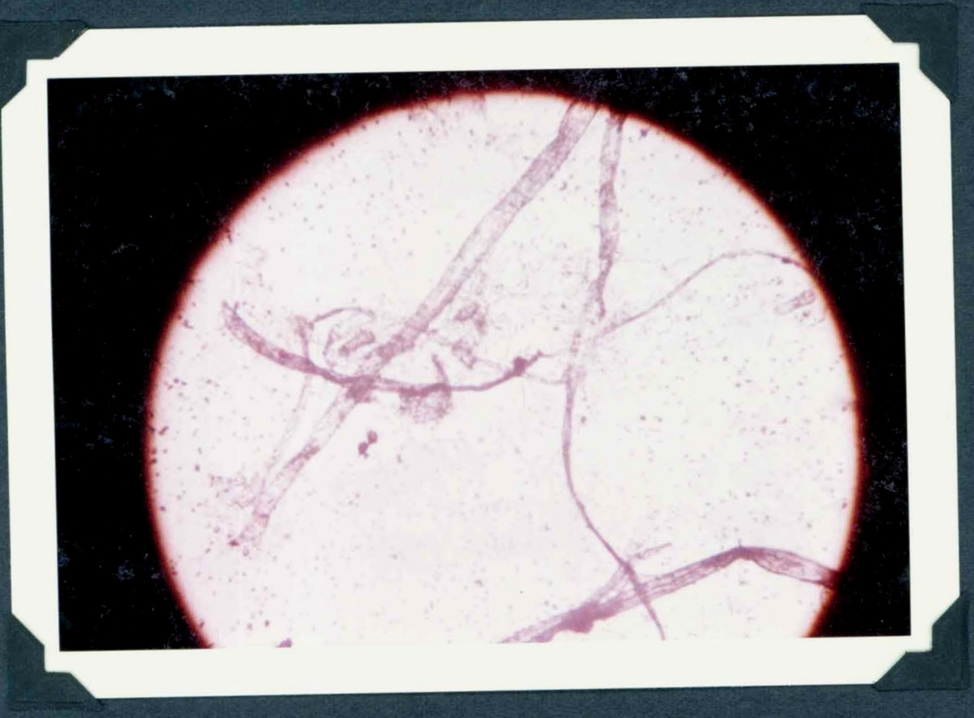


Fig. 9 - Control pulp (Pulp A) - showing raw untreated form of a western softwood sulphite pulp - x 100, f/2.8

Fig. 10 - Cut constituent (Pulp B) - showing high degree of cutting, with minimum fibrillation development - x100, f/2.8.



<u>Fig. 11</u> - Fibrillated constituent (Pulp C) - showing high degree of fibrillation and mucilage formation, with minimum cutting action - x 100, f/2.8.