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THE MORPHOLOGY OF CELLULOSE FIBERS AS
RELATED TO THE MANUFACTURE OF PAPER

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R 1084

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Abstract

The morphology of cellulose fibers as depicted by different research workers is described.

Both generally accepted and controversial views regarding the morphology and some of the attendant physical properties of fibers are briefly discussed. Among them are the interpretations of published results regarding (1) fiber substructures isolated by chemical means: layers, fibrils, fusiforms, spherical units, ellipsoids, dermatosomes, crystallites, and primary-valence chain; (2) unit cell of the crystal lattice of cellulose; (3) chemical nature of the interfibrillar material; (4) nature of the interfiber bonds in paper; (5) internal and external shrinking and swelling of fibers; (6) effect of previous chemical and mechanical treatments on the chemical dissection of fibers; and (7) the effect of beating on some of the physical properties of fibers.

Shape and structure are important properties to be considered in the evaluation of cellulose fibers for papermaking. Accordingly, the more that is learned about the shape and structure and the attendant properties of fibers the greater will be the probability of improving and developing paper products. This paper discusses some of the fundamental morphological properties of fibers in relation to their influence on papermaking.

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Size and Shape of Fibers

Cellulose fibers that are utilized for paper are slender capsular-shaped bodies. The average length of cotton, flax, and hemp fibers is about 35 mm., which is approximately 1,200 times their average diameters; the average length of hardwood fibers is 1 mm.; that of softwood fibers 3 mm. In general, the length of wood fibers is about 100 times their respective diameters. Straw pulp is composed principally of bast fibers, the average length of which is about 100 times their average diameters. They are very slender with pointed ends; their walls are drawn together at irregular intervals, giving the appearance of joints. Intermixed with the bast fibers are epidermal cells having serrated edges and also pith cells having smooth thin walls. Those from the pith vary from round to oval shape.

Fibers from different sources differ from one another, not only in size but also with respect to shape and other characteristics. As a result of these differences the fibers in papers and pulps containing fibers from two or more of most of the raw materials can be identified microscopically. For example, it is possible to distinguish among the fibers from cotton, flax, hemp, straws, cornstalks, bagasse, hardwoods, and softwoods. However, due to the similarity of the fiber characteristics it is difficult to identify mixtures of hardwood fibers or softwood fibers when they are present in the same pulp.

Cellulose fibers of various shapes and markings are present in a single paper-making raw material. Especially in wood, the type of fiber seems to depend on the season during which it develops and also on its function in the raw material. Some fibers gradually taper to pointed ends; some have rounded ends; and others are exceedingly blunt (Figs. 1, 2, 3). Some fibers are thick-walled with slender cavities and others are thin-walled with large cavities (Fig. 4). Those with thin walls develop during the early growing season when the moisture in the soil is plentiful; those with thick walls, in the latter part of the growing season when the soil moisture is less plentiful. They are, accordingly, named springwood fibers and summerwood fibers, respectively. In chemical pulps the springwood fibers generally collapse into ribbon-like structures, whereas those of the summerwood remain inflated. Springwood fibers tend to impart flexibility to the paper sheet; those from summerwood produce a stiffness, as has been observed by the Forest Products Laboratory and demonstrated by Nilsson (13), who compared test sheets made from both springwood and summerwood pulps.

In the radial direction springwood fibers are about twice as broad as adjacent summerwood fibers. The walls of springwood fibers are more abundantly provided with pits than are summerwood fibers. As a result, springwood fibers are weaker than those in summerwood. Nilsson (13) has shown that pulp fibers from springwood are more easily ruptured and frayed in the pulp beater than are those from summerwood. In addition to the pits, the cell wall of wood fibers is characterized by promiscuously spaced cross markings which result from slip planes between the cellulosic microstructural units. These markings produce a weakened condition in the wall structure. Such weakened places in the wall are more readily attacked and dissolved by cellulose solvents than the intermediate portions. Hence treatment of fibers with cellulose solvents, under properly controlled conditions, results in the segmentation of fibers into cross sections. Except for their slightly frayed ends they resemble cross sections cut by mechanical means.

Cotton and Manila hemp fibers are likewise characterized by microscopically visible slip planes arranged more or less at right angles to the long fiber axis. As a result of the weakened places at the markings, these fibers are also dissectible into cross sections by chemical means.

Flax and hemp fibers, on the contrary, contain knot-like markings in which the slender microstructural cellulose units appear to bend in the form of a tiny whorl called a knot. To the author's knowledge little is known concerning the relative resistance of these knots and the intermediate segments of the cell wall to cellulose solvents. It would seem that the whorls would form a loose, weakened structure.

It is common knowledge that fibers from cotton, flax, and hemp are too long for the formation of uniform sheets on a paper machine. Consequently, they require processing to shorten them previous to their being utilized in pulps, on the other hand, is suitable for sheet formation. They are processed principally for improving strength properties.

paper. The size of fibers in cornstalks, straws, and wood, pulps

Microstructure of Fibers

Before describing the various substructural units that have been reported in the literature it is important to refer to the views of Bailey and Kerr (1) on the reported substructures of the cell wall. They have examined a large number of tropical woods and have found a decided variation in the cell wall among different species of woods. For

instance, both concentric and radial stratifications were
found, the first type of arrangement having been reported by
a large number of workers and the latter by Dadswell (5).
They conclude that only a small number of woods have fibers
containing concentric sleeves; further, they content that all
the microstructures smaller than the sleeves are shredded
particles from a continuous cellulose matrix. Their conclu-
sion is based on the observation that no cleavage planes
suggesting the fiber substructures in question are micro-
scopically discernible. They seem to have failed to consider
that the discontinuities between the minute substructures are
naturally below the resolving power of the microscope until
after the bonds of the interfaces are broken by chemical and
mechanical means.

Contrary to the views of Bailey and Kerr, cellular
microstructural units have been isolated and photographed.
They are believed to be units rather than fortuitous particles
because they are rather uniform in size and shape and they
separate from one another when the fibers are treated accord-
ing to a well-controlled procedure. In various published
reports they have been classified under the following headings:
cell-wall layers or sleeves, fibrils, fusiforms, spherical
units, ellipsoids, and dermatosomes.

Cell-Wall Layers

Rarely in woods of the United States are cell-wall
layers distinguishable before the fiber has been subjected to
rather drastic alternate treatment with acids and alkalies.
During these treatments some of the hemi-celluloses are dis-
solved and the fiber undergoes swelling and shrinking if the
proper amounts of acids and alkalies are employed. As a
result of these manipulations, a number of concentric layers
or sleeves comparable in arrangement to those in onions may
become visible in cross sections of the fiber. On a longi-
tudinal surface of the fiber the layers appear as lines
paralleling the outer and the inner longitudinal boundaries
of the cell wall (Fig. 5). In reality, those sleeves are
thin-walled capsular bodies concentrically arranged. As a
result of that arrangement the sleeves cannot be separated
readily, even though they have been loosened from one another.
Separation can best be accomplished in fiber segments cut to
expose open ends so as to allow telescoping movement of the
sleeve segments (Fig. 6), or cut longitudinally through the
lumen to expose trough-shaped segments.

The number of sleeves in the cell wall apparently
varies from fiber to fiber and also with the thickness of the

walls. The author has noted as many as twelve in some fibers,
and even more have been reported by Scarth (17). To dis-
tinguish them requires a replacement of hemicellulosic mate-
rials between them with aqueous solutions having an index
of refraction differing from that of the sleeves. The next
succeeding smaller unit into which the fiber can be dissected
is a slender cellulosic filament called the fibril.

Fibrils

Although the different cell-wall layers of normal
wood fibers appear as homogeneous sleeves, they nevertheless
are composed of compactly wound cellulosic filaments, named
fibrils. A smooth sleeve results from a filling of any inter-
stices between the fibrils with hemicellulosic material which
in normal fibers must be removed before the fibril windings
become discernible. In the outer layer of the cell wall the
windings are arranged at approximately right angles to the
fiber axis (Fig. 7). That the striations shown in Fig. 7 re-
sult from windings of filaments rather than a wrinkling of
a homogeneous sheath is demonstrated in Fig. 8 in which the
helical structure is proved beyond a doubt. This finding is
contrary to the explanation suggested by Trogus (23), who
apparently failed to discover the fibril structure of the
outer sheath. Unlike the fibril arrangement of the outer
sheath, that of the remaining sleeves of the secondary cell
wall of normal wood fibers is from 5 to 30 degrees to the
long fiber axis (Fig. 9).

It may be noted in Fig. 7 that intense swelling of
the fiber occurs where the outer layer has been removed, mak-
ing the remainder of the fiber appear constructed. This
phenomenon indicates that the outer layer restricts transverse
swelling of the fiber. The same is well illustrated in Figs.
10 and 11. In these illustrations the swelling agents have
forced the secondary cellulose layers between the windings
of the outer sleeve, rolling them over one another. In this
manner there may be formed short constrictions which are
wrapped by several thicknesses of the constricting sleeve.

In spite of the drastically swollen condition, the
secondary sleeves can be traced through the constricted and
the beaded segments (Fig. 11). These results indicate that
the cell-wall layers have no transections, which is contrary
to the views of Lüdtke (11) and Lewis (10), who contend that
the fiber is segmented at short intervals by cross walls
which prevent transverse swelling of the fiber at the cross
walls. The absence of cross walls may be further demonstrated
by mechanically rupturing the constricting sheath between two

of the beaded segments. When that is done the two beads are converted into a single large spheroid having no transverse breaks in its wall. Still other additional evidence to prove the absence of cross walls is presented in the form of fibril sections 230 microns long from the secondary layers (Figs. 12 and 13). These dimensions are approximately six times the average distance (40 microns) between the cross walls according to Lüdtke.

Fibril segments of 230 microns are only short portions of the units. The difficulties encountered in isolating the entirely intact fibrils, however, are not due to intersections with cross walls but rather to the fragility of the filaments. Consequently, the mechanical force required to separate them, even after loosened by chemical means, is in many cases sufficient to break the slender structures.

Fibrils are loosened from fibers during the beating of chemically prepared pulp but before they separate other effects which improve the strength of the paper made from the beaten pulp are produced. Although the effects continue to increase concurrently, after a certain stage is reached in the beating process, they generally begin development in the following order: increase in the pliability of the fibers, transverse cutting of the fibers, gelatinization of fiber surface, rupturing of outer layer, fibrillation, and increase of translucency. This order of development may differ depending on the method of operating the beater.

An increase in fiber pliability is considered advantageous in obtaining a suitable formation of paper because it increases the number of fiber-fiber contacts, thereby increasing the density and strength of the paper. As reported by Doughty (6), transverse cutting or shortening of the fiber generally aids in the formation of more compact sheets and likewise increases the number of fiber-fiber contacts. An exception, of course, is the result obtained by the quick cutting process of producing blotting and book papers. By this procedure fibrillation is kept at a minimum and increase in flexibility is not increased to any marked degree. Gelatinization of fiber surface is produced by the initial loosening of the interfibrillar material on the fiber surface. Rupturing of the outer layer exposes the fibrils of the inner sleeves to the beating action which produces "brooming" of the fibers, thereby improving felting during sheet formation on the fourdrinier (Fig. 14). This stage of beating tremendously increases the number of fiber-fiber contacts.

It is obvious that an increase in the number of fiber-fiber contacts without destroying the gross fiber structure is essential for improving the strength properties of the

sheet. This is indicated by observations made by Simmonds and Baird (19), who used rubber balls as processing elements. On the other hand, too prolonged beating will greatly reduce the fibers, producing an oversupply of short segments at the expense of the gross fiber structure. As a result, the increased number of fiber segments requires a greater number of fiber-fiber contacts. Since the mechanically made bonds are weaker than those within the fiber structure, as is demonstrated by their greater reactivity to moisture, sheets made from overbeaten pulp are therefore weaker than those made from pulp beaten the optimum time.

Papers having a high degree of opacity contain both interfiber and intrafiber (cell cavity) voids. Prolonged beating tends to eliminate the interfiber voids in sheets through the utilization of the finely divided cellulosic particles as a filler. It excludes the intrafiber voids or cell cavities also by destroying the gross fiber structure. As the voids are gradually excluded the paper becomes more and more translucent because fewer randomly arranged fiber-air interfaces remain for interference with the normal transmission of light through the paper.

The mechanism of the forces operating in the fiber-fiber bonds is a moot question. Strachan (21), Mark (12), Harrison (8), and others believe that the tenacity of the bond is a cementing force produced by dehydrating the gelatinized surfaces of the more or less intact fibers and fibrils. This explanation requires no agreement in the alignment of the cellulosic particles in the two adjacent surfaces. Campbell (3), on the other hand, contends that the holding power is the result of crystallographic forces developed during the dehydration of the bonds. His concept of the force in the bond necessitates a preferred rearrangement of the cellulosic crystals to take place in the two gelatinized surfaces as dehydration proceeds. Both schools of thought agree that a cohesive force manifests itself when the water is evaporated from the gelatinized surfaces. It then seems that the main difference regarding the nature of the bonds is one of terminology. As yet there is a scarcity of data to prove whether the cellulose particles of the bonds are randomly arranged as characteristic of a cementing force or regularly aligned according to some crystallographic system.

As has been shown, the loose ends of fibrils play a role in the felting properties of paper sheets. If fibers are properly treated (14) long fibril segments are isolated (Fig. 15). Their full length is by no means measurable from the photomicrographs since the slender filaments have been broken into short sections during the isolation procedure.

Fusiforms

Under closely controlled conditions (14) fibrils have been dissected into slender spindle-shaped structures which have been named fusiforms (Fig. 16). Before their separation these structures are arranged with their pointed ends overlapping to build up the fibrils.

Spherical Units

Fusiforms from wood (15) are composed of tiny units which assume a spherical shape when they separate from one another (Fig. 17). As near as can be measured, the spherical units range from 0.2 to 0.4 microns in diameter as isolated in an extremely swollen condition. Although they are spherical in shape when isolated, they nevertheless must be ellipsoidal or oblong in the fusiforms as is shown by the contrast in the optical properties of the two types of structural units. In polarized light they manifest random arrangement of their crystalites, whereas the fusiforms manifest parallel arrangement of their crystallites. The contrast can be explained on the basis of a change from preferred to random orientation of the crystallites in the spherical units during the isolation process. That is highly probable because the procedure involves intense swelling of the cellulose particles.

Ellipsoids

Farr (7) has succeeded in isolating ellipsoidal units from cotton fibers (Fig. 18). They are 1.0 by 1.5 microns in size, being three and one-half to seven times the size of the spherical units. They are doubly refractive to light, in which respect they are comparable to the fusiforms, although they are thicker and shorter than the drastically swollen fusiforms. Having been found in the cytoplasm in the developing cotton fibers they should be at their natural water-saturated size. On the contrary, the fusiforms and the spherical units from wood when isolated are in an extremely swollen condition, being at least 100 percent or more greater than their normal size. The author appreciates that such minute measurements are difficult to make. Taking the thickness dimension, as reported, of the ellipsoids in a water-saturated condition, it seems difficult to reconcile it with the thickness of fibrils or even the cell-wall sleeves as reported by other research workers.

Dermatosomes

Wiesner (24), by means of heated hydrochloric acid solution, has broken down cellulose fibers into dust-like particles which he believes are microstructural units (Fig. 19). He has named the particles dermatosomes. So far the author of this paper has not convinced himself that these are actual structural units.

Supermicelles

Seifriz (18) and Thiesen (22) claim to have discovered by means of the Spierer lens a microstructural unit which has not been isolated. The unit has been named supermicelle by Zeifriz and micelle by Thiesen on account of its shape, resembling that of the micelle postulated from X-ray data. On the contrary, Ritter (16) and Clifford and Cameron (4) believe the supermicelles are nothing more than diffraction bands.

Ash Residue

The microscopically visible units described above are principally organic or cellulosic in composition. If the fibers are burned rather than dissected, an inorganic residue or ash is left. Even though the ash constitutes only a fraction of 1 percent of the fiber, it still forms a continuous structure which represents a skeleton of the fiber (Fig. 20). No definite conclusions have been reached regarding the combination of the ash in the untreated fibers.

Submicrostructure of Fibers

Micelles or Crystallites

Structural units below the resolving power of the microscope have been conceived from X-ray data. The largest of these has been named micelle or crystallite. In shape it is believed to be a rectangular parallelopiped, being approximately 50 by 50 by 500 to 1000 Angstrom units in size (Fig. 21). The micelles are supposedly held together by tertiary valence forces. Whether other physical structures exist intermediate to the spherical units and crystallites is not known.

Primary Valence Chains

Primary valence chains are substructures of the micelles. They are long, slender structures, being from 500 to 1000 Angstrom units in length (Fig. 21). They are composed of anhydroglucose residues attached through an oxygen bridge between carbon 1 of one sugar residue and carbon 4 of the succeeding sugar residue. The primary valence chains are held together by secondary valences to form the rectangular bundles, micelles or crystallites.

Unit Cell

The unit cell is a regularly occurring unit diagram in the crystal lattice. It involves the glucose residues of the primary valence chains, comprising the equivalent of four anhydroglucose residues -- two whole residues and eight quarter residues (Fig. 22). Unlike the foregoing structural units, which are composed of one or more whole physical structures, the unit cell is a theoretical reoccurring spacing which includes both whole and fractional parts of physical structures. Its dimensions, which are 7.8 by 8.3 by 10.3 Angstrom units, are calculated from X-ray diffraction data.

Physical Properties of Cellulose Fibers

Shrinking and Swelling

It is a well-known experimental fact that the sorption of water by wood below fiber saturation causes shrinking and swelling. Likewise chemically isolated cellulose fibers manifest similar properties. These volume fluctuations are caused by the sorption of water in the interstices between the various structural cellulose units even as small as the crystallites. The measurement of the moisture-volume relation of wood and isolated fibers is complicated by the fact that a part of the change in volume is internal. The internal volume changes are difficult to determine because they involve dimensional measurements of the lumen and the intercellular spaces. Direct measurements of the lumen before and after sorption of water can be made on fibers of properly selected cross-sectional shape, but those of the intercellular spaces are hopelessly complicated. Fortunately, the effect of the intercellular spaces can be minimized by utilizing wood sections involving very few of these cavities and better still, it can be eliminated entirely by choosing isolated fibers.

An approximate measurement of the changes in the volume of fibers is simplified by considering their lengthwise behavior when water is sorbed. Repeated measurements reveal that the fluctuation in the longitudinal dimension of wood and isolated fibers is only a fraction of 1.0 percent. Wood blocks are prone to increase slightly and isolated fibers to decrease slightly lengthwise when water is absorbed. This contrast in behavior as exhibited by wood and isolated fibers is explainable in that the long axis of all the fibers is not parallel with that of the wood. Consequently, if the transverse swelling of the nonparallel fibers is resolved into its two components, a slight longitudinal swelling occurs even in small wood sections. Also a swelling of the wood rays tends to increase the longitudinal dimensions of wood. Since the longitudinal fluctuation of isolated fibers is so slight, it is necessary to consider only the cross-sectional measurements in approximating the volumetric swelling. Such a procedure will result in volumetric swelling values that are slightly low for wood and slightly high for fibers.

It is on the basis of omitting the longitudinal measurement that the internal and external swelling of partially delignified fibers was approximated. The results were collected microscopically several years ago. Although limited in scope, they positively reveal that the internal swelling is considerable and varies from fiber to fiber.

Cross sections of spruce wood 25 microns thick were partially delignified. The cross sections of fibers were still attached at irregular intervals so as to keep them from falling apart. The sections were placed on microscope slides and oven dried. Days having low relative humidities were chosen for making the microscopical measurements of the dry cross sections. Next water was allowed to flow over the sections and the dimensions of the water-soaked material were again measured.

Data for approximating the percentage of swelling consisted of the external dimensions and the lumen dimensions of the dry wood cross section, the external dimensions and the lumen dimensions of the water-soaked wood cross sections. (Fig. 23.)

Calculations of the swelling were made according to the following formulas:

$$\left[(a \times b) - (c \times d)\right] = \text{dry volume of wood}$$

$$\left[(a' \times b') - (c' \times d')\right] = \text{wet volume of wood}$$

$$\frac{[\text{Wet volume} - \text{dry volume}] \times 100}{\text{Dry volume of wood}} = \text{Percent total swelling}$$

$$\frac{[(c \times d) - (c' \times d')] \times 100}{\text{Dry volume of wood}} = \text{Percent internal swelling}$$

$$\frac{[(a' \times b') - (a \times b)] \times 100}{\text{Dry volume of wood}} = \text{Percent external swelling}$$

Calculations from the foregoing formulas indicate that the total volumetric swelling based on the dry volume ranges from 38.0 to 46.5 percent, the external swelling ranges from 25.0 to 30.0 percent, and the internal from 8.0 to 13.0 percent. The lower values for the total percentage swelling can be explained on the basis of some moisture being absorbed before the measurements of the dry sections were completed.

The data further indicate that during drying the shrinkage of the outer sleeve, which in effect amounts to its longitudinal contraction, is insufficient to accommodate the crosswise contraction of the remainder of the cell wall. To compensate for the discrepancy, the tiers of fibrils adjacent the lumen are drawn outward, thereby increasing the size of the lumen and setting up a strain. When dry fibers absorb water, both internal and external swelling occur, restoring the lumen to its original size and thereby relieving the strain set up during drying.

Values for the internal swelling presented in this paper are greater than the calculated cross-sectional changes in the cell cavities of untreated wood sections reported by Stamm (20) and the changes given by Beiser (2). Just what effect lignin ray cells and neighboring fibers have on swelling is unanswered from the available data. That question is, perhaps, beside the point for the paper manufacturer. He is, however, interested in the two types of swelling manifested by isolated fibers since both of them affect the density of the paper.

Internal swelling of an exaggerated type occurs when swelling agents, such as dilute sodium hydroxide and potassium hydroxide solutions, are employed. These reagents convert the angular-shaped fiber cross section to a ring. Even in the ring form the perimeter of the fiber is too short to accommodate the extremely swollen condition of the secondary cell wall. Unable to stretch the outer sleeve farther, the

reagent forces the secondary cell wall into the lumen, there-
with closing it entirely (Fig. 24).

Just why dilute alkaline solutions swell wood more
than does water can be explained in several ways. The most
probable explanation is that the alkaline solutions penetrate
into interstices which are inaccessible to water as such.
For example, Katz (9) has demonstrated that alkaline solutions
permeate into the crystallites, whereas the smallest inter-
sticial spaces into which water as such penetrates are those
between the crystallites. Naturally, the increased number of
voids involved will greatly increase the swelling. Then, too,
the X-ray data indicate a change from parallel to random ar-
rangement of the crystallites during swelling with alkalies,
which would increase the transverse dimensions and decrease
the longitudinal dimensions of the fibers.

Compression Fibers

Some fibers like some woods manifest abnormalities.
A common irregularity affecting their physical appearance is
known as compression. It consists of a more or less loose
winding of the fibrils, making them distinguishable without
the application of chemicals (Fig. 25). For some unknown
condition, the fibrils are openly spaced with intervening
checks which extend through the secondary thickening of the
cell wall. In general, the fibril slope ranges from 30 to
40 degrees to the fiber axis. In cross sections of fibers
the checks appear as radical ruptures extending from the lumen
to the outer layer. Another characteristic of compression
fibers is noticeable in untreated cross sections of wood. It
is the abundance of intercellular spaces. They result from
the rounded fiber corners which fail to bond with their
neighbors. Due to the open structure of compression fibers,
they are readily fibrillated by chemical means and should
likewise disintegrate easily by mechanical means, such as the
beater.

Resistance to Fibrillation

Other factors being the same, the resistance of
fibers to fibrillation depends on the severity of their pre-
vious chemical and mechanical treatments. In other words,
fibers from a pulp prepared by a drastic pulping process
dissect more easily than those from a pulp prepared by a mild
process (Fig. 26). Also the fibers from a pulp that has re-
ceived drastic mechanical treatment dissect more readily
than those in a pulp having received little mechanical pro-
cessing (Fig. 27). These results are explainable on the basis

that a greater percentage of the interfibrillar substance is loosened and removed by the more severe treatment than by the milder treatments. This explanation may seem contrary to the well-known experimental fact that alpha pulp is dissected and fibrillated with greater difficulty than a less purified pulp. That, however, occurs when the alpha pulp has been dried, allowing the modified cellulose materials to cement the fibrils together by a substance more resistant than that in the original fibers.

Much has been written about the interfibrillar substances but little definite information is available regarding its composition. It is hydrolyzed and dissolved in less concentrated acid and alkaline solutions than the major portion of the fibrils, which is composed of the more stable or longer primary-valence chains.

In wood, straw, and cornstalk fibers, it seems to consist of compounds consisting of uronic acids, pentosans, and hexosans. During fibril development it precipitates from the cytoplasm after the more insoluble longer-chained polysaccharides of anhydroglucose residues. If this view is tenable, then the more stable cellulose would form the fibril central core which would be insulated with the interfibrillar material. In cotton it might consist of anhydrouronic acids and anhydroglucose residues combined in the form of compounds of a lower molecular weight than the stable cellulose. Such an interfibrillar hemicellulosic material will exhibit the chemical and physical properties cited by Lüdtke (11) for a skin substance which he postulates as surrounding the various cellulose units.

An interfibrillar substance as just described would, for example, evolve carbon dioxide when heated with boiling hydrochloric acid. Physically it would form a continuous matrix between and surrounding at least the larger microstructural cellulose units. If its continuity were severed between the cellulose units by chemical and physical means, the units could be separated. Strong swelling agents would cause it to swell and stretch so as to accommodate the swelling action of the encased more stable cellulose particles.

Types of Dissection

Fibers dissect differently, depending on the severity of their previous chemical treatment. If they still contain the interfibrillar material and considerable lignin in the outer sleeve, they dissect according to Fig. 10. On the contrary, if they have been well delignified during which some

of the interfibrillar substance of the outer sleeve has also been removed, they dissect according to Fig. 28. In the first case the lignin retards solution of the outer layer, resulting in a beaded effect at irregular intervals where rupturing between the windings occurs. Many of the constrictions resist solution even on increasing the dissecting agent to a concentration that readily dissolves cellulose. In the second case, the outside layer dissolves uniformly, allowing the inner sleeves to fibrillate uniformly. As a source for rayon a pulp exhibiting the properties of the latter fiber would seem the more desirable because all of the lignin and much of the hemicelluloses have been removed.

Summary

Cellulose fibers are described from the standpoint of their morphology and its influence on their papermaking properties. Cotton, flax, and hemp fibers require processing for the development of both sheet formation and strength properties. Wood, straw, and cornstalk fibers require processing principally for developing strength properties.

Structural properties, both the micro and the submicro of the various kinds of fibers, with special emphasis on those of wood, are discussed. These properties and their attendant physical characteristics manifested by fibers in the manufacture of pulp and paper are described and illustrated by means of photomicrographs.

An interfibrillar material is discussed from both the chemical and the physical standpoint, together with its apparent effect on the behavior of fibers during the processing of pulp previous to the manufacture of paper.

Measurements of the internal and the external swelling of isolated wood fibers are given. They show that a substantial part of the swelling is internal.

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Description of Photomicrographs

(See opposite page for illustration)

Figure 1.--Delignified cellulose fibers having pointed ends.

Figure 2.--Delignified cellulose fibers having ends of various shapes.

Figure 3.--Delignified cellulose fibers having rounded and blunt ends.

Figure 4.--Transverse sections of springwood and summerwood fibers.

Figure 5.--Delignified wood fibers, the layers of which have been loosened from one another.

Figure 6.--Sections of delignified wood fibers, the cell-wall layers of which have been partially separated by slipping them endwise.

Figure 7.--Windings of the fibrils of the outer layer of a wood fiber showing the extreme transverse swelling of the remainder of the cell wall from which the outer layer has been removed.

Figure 8.--Outer layer removed from a delignified spruce wood fiber and stretched slightly endwise.

Figure 9.--Partially loosened fibrils of the inner layers of a delignified elm fiber.

Figure 10.--Windings of the outer layer of an incompletely delignified spruce fiber pushed apart by the extreme swelling of the inner layers.

Figure 11.--Shows the uninterrupted longitudinal structure of the individual layers of the secondary cell wall.

Figure 12.--Section of a delignified pine fiber in a fibrillose condition.
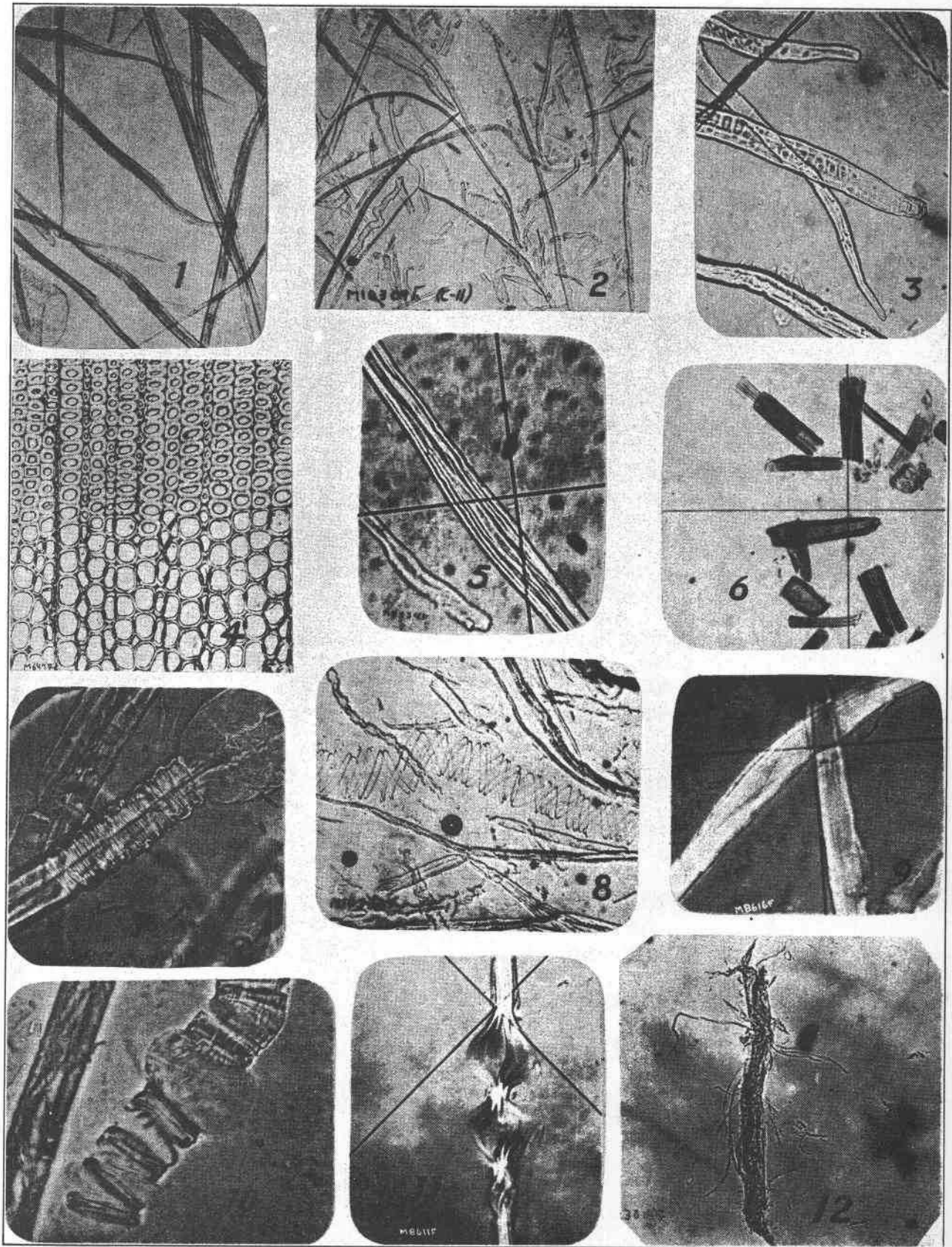
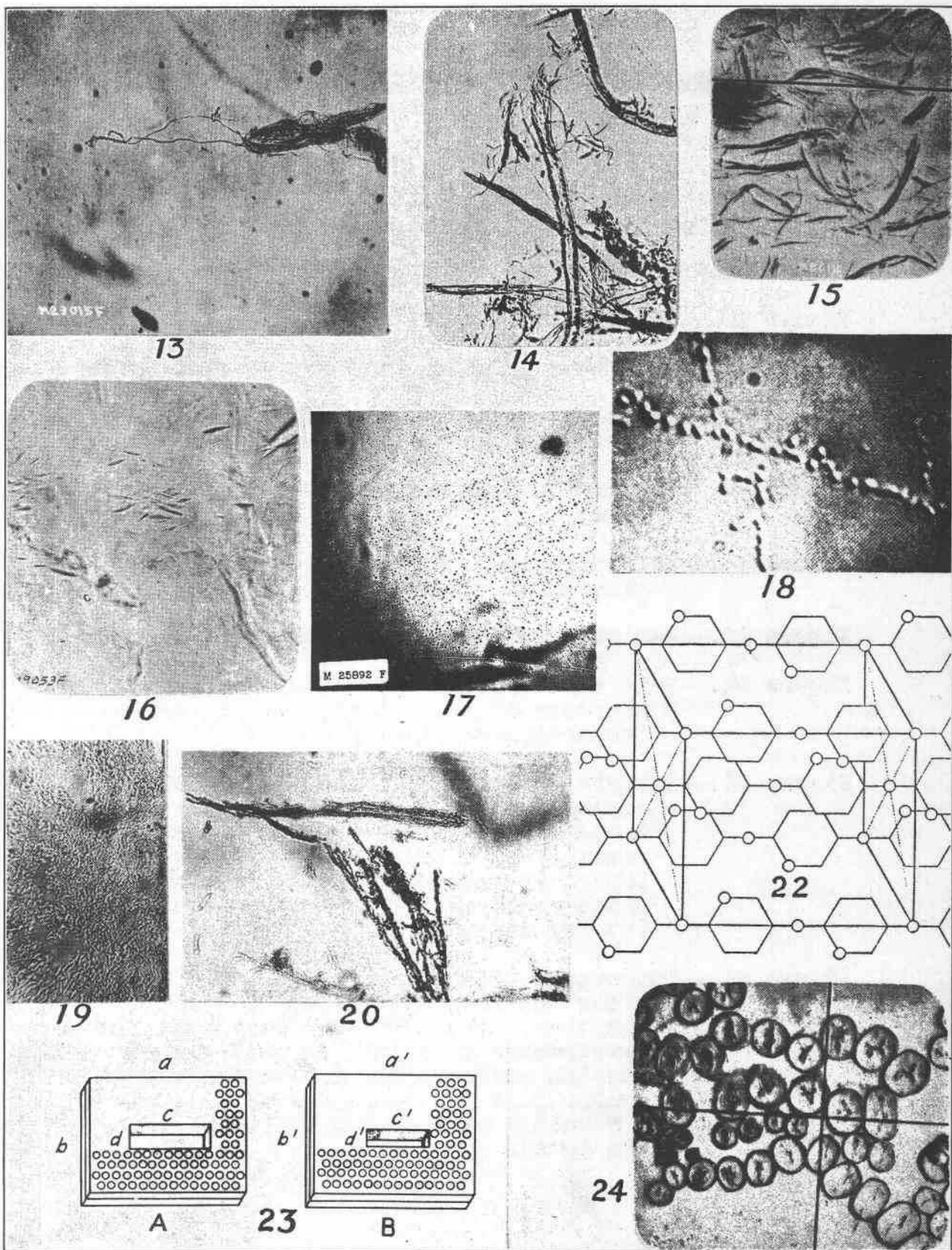4

FOR DESCRIPTIONS OF PHOTOMICROGRAPHS SEE OPPOSITE PAGE

Description of Photomicrographs and Diagrams

(See opposite page for illustrations)

Figure 13.--Section of delignified pine fiber from which a
long fibril section has been teased.

Figure 14.--Fibers showing different stages of fibrillation.

Figure 15.--Fibrils isolated from delignified wood fibers.

Figure 16.--Fusiforms isolated from delignified spruce fibers.

Figure 17.--Spherical units isolated from delignified spruce
fibers.

Figure 18.--Ellipsoids isolated from cotton (according to
Farr).

Figure 19.--Dermatosomes isolated from delignified fibers
(according to Wiesner).

Figure 20.--Ash residue from wood fibers.

Figure 22.--Unit cell showing the arrangement of the glucose
residues of the primary-valence chains
(according to Clark).

Figure 23.--Diagram of transverse sections of wood. The
arrangement of the fibrils in the outer layer is
indicated by the horizontal lines and the
arrangement of the fibrils in the remaining
layers is indicated by the rows of circles
which represent fibril cross sections.
(a) Dry section; (b) wet section.

Figure 24.--Transverse sections of delignified wood fibers
after swelling with dilute sodium hydroxide
solution. Although the cross-sectional faces
have become circular, the outer layer cannot
stretch sufficiently to accommodate the outward
swelling of the remainder of the cell wall. As
a result a part of the cell wall is forced into
the lumen.

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14

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22

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24

A   23   B

FOR DESCRIPTIONS OF PHOTOMICROGRAPHS AND DIAGRAMS SEE OPPOSITE PAGE

Description of Photomicrographs and Diagrams

(See opposite page for illustrations)

Figure 21.--Micelles or crystallites of cellulose indicating
the forces holding them together and showing
the arrangement of the primary-valence chains
in one of the micelles (according to Clark).

Figure 25.--A delignified isolated fiber from compression
wood shows the large fibrillar angle.

Figure 26.--Shows the influence of previous chemical treatment
on the dissection of fibers by chemical means.
36-0. Pulp prepared by a mild digestion, given
no milling and then treated with chemical
dissection agent. 26-0. Pulp prepared by a
drastic digestion, given no milling and then
treated with the same dissecting agent as pulp
36-0.

Figure 27.--Shows the effect of previous milling on the
dissection of fibers by chemical means. Pulp
26-0 received no milling but the same pulp 26-60
received 60 minutes milling previous to the
treatment with the dissecting agent. Note effect
of milling on the subsequent dissecting treatment.

Figure 28.--Shows the type of dissection that results if a
well delignified wood fiber is treated with a
chemical dissecting agent. Contrast with
Figure 10 to see the effect of incomplete
delignification.

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21

26

36-0

26-0

27

26-0

26-60

28

FOR DESCRIPTIONS OF PHOTOMICROGRAPHS AND DIAGRAMS SEE OPPOSITE PAGE